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Technical Report

No. 12703

FLEXIBLE MANUFACTURING
SYSTEM HANDBOOK
VOLUME VI: FMS DECISION SUPPORT
SOFTWARE CASE STUDIES
TACOM CONTRACT NUMBER DAAE07-83-C-R084
FEBRUARY 1986

By CHARLES STARK DRAPER LABS, INC.
CAMBRIDGE, MASSACHUSETTS 02139

U.S. ARMY TANK-AUTOMOTIVE COMMAND
RESEARCH, DEVELOPMENT & ENGINEERING CENTER
Warren, Michigan 48397-5000

20020814061

[redacted]

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution of Volume VI is unlimited. It may be obtained from: National Technical Information Service 5285 Port Royal Road Springfield, VA 22161
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) CSDL-R-1599	5. MONITORING ORGANIZATION REPORT NUMBER(S) 12703
6a. NAME OF PERFORMING ORGANIZATION Charles Stark Draper Laboratory 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Cambridge, MA 02139	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Army Tank-Automotive Command 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAE07-83-C-R084
8c. ADDRESS (City, State, and ZIP Code) Warren, MI 48090 Attn: AMSTA-RCKM	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT NO.

11. TITLE (Include Security Classification) Manufacturing System Handbook, Vol. VI, FMS Decision Support Software - Case Studies

12. PERSONAL AUTHOR(S)

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr/Mo/Day)	15. PAGE COUNT
Technical Report	FROM ______ TO ______	December 1984	122

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.
09	02	
13	08	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Flexible Manufacturing; Design and Evaluation; Simulation; Design Support; Modeling; Capacity Planning; Work Load Balancing; Cutting Tool Redistribution

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Flexible Manufacturing Technology is a means to increase productivity for manufacturing environments in the middle ranges of production volume. It is effective for "one of a kind" and true "mass production" quantities. Volumes I through IV of this handbook help determine if a flexible machining systems (FMS) will be cost effective for a given application. These volumes explain the configuration and procurement of a FMS, and its impact on the existing organization. Volumes V and V-A of the handbook detail the computer programs for the FMS in the form of User's Guides for some 10 separate modules. Volume VI consists of two

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Ivan S.C. Johnson	22b. TELEPHONE NUMBER (Include Area Code) (617) 258-3893 22c. OFFICE SYMBOL

DD FORM 1473, 83 APR   EDITION OF 1 JAN 73 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

Block 19 (Continued)

Case Studies documenting the use of the developed Decision Support software modules and related procedures for the design and evaluation of proposed and planned FMS's.

ACKNOWLEDGMENT

This report was prepared by the Charles Stark Draper Laboratory, Inc., under Contract DAAE07-83-C-R084 with the U.S. Army Tank-Automotive Command, Warren, Michigan.

Grateful acknowledgment and thanks are extended to the following U.S. Army personnel for their support and encouragement in the work reflected in this document:

Mr. David Pyrce, FMS Project Monitor, TACOM
Mr. Donald Cargo, Chief, Metals & Welding Sub-Function, TACOM
Dr. James Chevalier, Chief, Armor and Components Function, TACOM
Mr. John Wilkins, Rock Island Arsenal

and especially,

Mr. Frederick J. Michel, Chief, Manufacturing Technology, Army Materiel Defense and Readiness Command (DARCOM), Alexandria, VA

In addition, we wish to extend our appreciation to the following Army contractor personnel with whom we collaborated in this work:

Mr. Joel Schnur, Hughes Aircraft Company, EDSG, El Segundo, CA
Mr. Kevin Aaron, Hughes Aircraft Company, EDSG, El Segundo, CA
Mr. David Liu, Hughes Aircraft Company, EDSG, El Segundo, CA
Mr. Richard Fent, FMC Ordnance, San Jose, CA
Mr. Larry Martin, FMC Ordnance, San Jose, CA
Mr. Richard Dvorsky, Cincinnati Milacron, Cincinnati, OH
Mr. Vincent Rovito, Cincinnati Milacron, Cincinnati, OH

PREFACE

This document is a compendium of two application case studies focusing on the design and optimization of FMS operations, using Decision Support modules and related procedures established and applied under U.S. Army (DARCOM, TACOM) sponsorship during recent contract periods. Each case represents a complete study performed for a single client. Each case, however, pertains to a different client.

This document is part of a multi-volume series (the "FMS Handbook") written by C.S. Draper Laboratory, Inc., Automation Systems Division, to address technical issues fundamental to the design, development, and operations of Flexible Manufacturing Systems (FMS's).

The reader will understand the contents of this volume significantly better having read Volumes V and V-A of the Handbook. Those volumes consist of User's Guides for the Decision Support modules referred to in the present volume.

Volumes V and V-A are under distribution control by the U.S. Army. Requests for authorization to receive Volumes V and V-A may be addressed to:

Mr. David Pyrce
U.S. Army Tank-Automotive Command
Attention: AMSTA-RCKM
Warren, Michigan 48090

or by direct communication with:

Defense Technical Information Center (DTIC)
Cameron Station, Bldg. 5
Alexandria, Virginia 22314

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1.0 OVERVIEW

1.1 DESIGN AND EVALUATION METHODOLOGY

This FMS design and evaluation effort was performed in two phases: Phase I, Part and Machine Selection; Phase II, Configuration Design and Evaluation. During Phase I (conducted in 1981 and 1982), we evaluated approximately 4,200 parts currently manufactured by client for applicability of FMS technology. Part size, material, processing requirements, final end items and other factors were considered. Over 200 different categories of machines were examined to determine which client machine classes performed tasks that an FMS could perform. 4,056 parts were eliminated from consideration due to physical properties or processing requirements. More than 120 machine classes could be merged into ten general FMS machine groups.

Detailed part/machine selection using linear programming algorithms and part manufacturing cost estimates indicated that, of the 144 candidate parts, 40 to 70 would have to be selected to fill an eight- to ten-machine FMS (the size client thought they could control and afford). It was found that only machines from three machine groups -- small, medium and large machining centers -- could be assigned enough work from the 144 parts to be included economically in an FMS. Applying the constraint that any parts with fewer than 200 annual production hours would be eliminated (due to minimal savings contribution) left 60 parts for final consideration.

Phase II, Detailed FMS Design and Evaluation, was pursued based on the preliminary economic study indicating that an eight- to ten-machine FMS could be economically beneficial for production of the 60 candidate parts. A payback period of less than four years appeared likely.

Client accepted this recommendation and requested that Phase II begin. FMS Design and Evaluation began with detailed process planning of each candidate part to determine its suitability and cycle time. Fixture concepts were developed for each part. Two types of machines were considered: horizontal machining centers, indicated as economically justifiable in Phase I, and vertical turret lathes. The VTL's did not have enough work to justify purchase, but could be justified when combined with Machining Centers since the parts could then be machined completely in the FMS. The fixture concepts for each part were reviewed by client and accepted.

Elemental process planning was then undertaken for each part, determining the exact processing sequence, cutting tools, part orientation, and cycle time per machine. Eight parts were eliminated due to processing difficulties. One part was added from the "Less than 200 Hour" category due to its FMS processing advantages. These plans were reviewed by client personnel and accepted. The theoretical machine load, based on the work content of the parts, the number of production hours per year and an expected system efficiency was calculated next. Client decided normal procedure would be to operate two (2) eight-hour shifts, 240 days per year. We used 75% as assumed FMS efficiency, based on current FMS user experience. Thus, four horizontal machining centers, one vertical turret lathe, and two load/unload stations theoretically were required by the 53 parts.

FMS machines have limited on-machine tool storage. To determine whether the parts can all be produced concurrently in the FMS or must be divided into smaller parts groups, we used tool distribution and work load balancing software developed by Draper automation systems engineers specifically for FMS analysis. This showed that the 53 parts would have to be divided into two parts groups, i.e., not all parts could be produced concurrently. The parts were selected for each parts group to obtain the most balanced workload across the machines and meet delivery dates. The software assigned parts and tools to specific machines in the FMS; this provided the data for modeling and simulation of the FMS.

FMS modeling is essentially simple and cheap simulation, based on queuing theory. Modeling indicates the proper number of each type of station in the FMS required at steady state operation (validating the theoretical machine load calculations), the average number of parts waiting for any station, the approximate number of piece parts to process in the system at any given time, approximate number of available fixtures for each part, and the number of transporters required. Draper's modeling tool provides three performance measures for each FMS design: each machine's utilization (i.e., average percent of time in tape), average time a part is in the system, and part type by part type production rates. Using these measures, numerous designs can be analyzed quickly and inexpensively; only the one or two best designs need be simulated in detail.

FMS simulation replicates in detail the expected operation of the FMS after installation. Simulation requires an (at least preliminary) FMS floor plan and scheduling and dispatching policies that will be used to control the flow of parts through the FMS. Simulations of the final FMS design indicated the number of copies of each fixture type required for each part, the utilization of all components of the system, and the production rate for each part. All parts could be made in the proper quantities within 75% of the available operating hours for the system.

Economic analysis was performed to determine the Return on Investment (ROI) and payback period of the final FMS design. The FMS design was compared to the alternative of buying a production-equivalent number of stand-alone CNC machines in two analysis categories: (i) capacity expansion (the case at client), and (ii) machine replacement (from two viewpoints).

The FMS, as designed, including an integrated inspection robot, automatic storage and retrieval system, tools, pallets, fixtures and installation would cost about $8,216,000. The equivalent number of stand-alone machines, based on an estimated client NC-shop efficiency of 34.2%, is 10; they would cost about $9,816,000.

Calculating the manufacturing cost for each alternative required more assumptions, primarily on how to allocate the correct proportion of fixed overhead to the FMS. The standard allocation basis is floor space. It was assumed that the FMS would be allocated fixed overhead based on its share of floor space - the remaining space would be utilized by other equipment to which the remaining fixed overhead would be allocated. The floor space and fixed overhead required by the stand-alone alternative used the present nominal space and allocated costs. The FMS would use approximately half the floor space of the stand-alone alternative, and therefore was assigned only half the fixed overhead of the stand-alone case.

The manufacturing cost for the FMS was $1,142,514 and $2,614,563 for the stand-alone case in the first year. Since the FMS was both the smaller investment and the lesser production cost method, it appeared to be the better choice from a capacity expansion analysis standpoint.

For the machine replacement analysis, the manufacturing costs for both alternatives are assumed to increase at the rate of 7% annually. If no equipment were sold to offset the cost of the FMS, FMS Return on Investment (ROI) before taxes ranges from 30% if the parts will be produced for ten years to 17% if the parts will be produced for five years. If machines can be sold to offset the cost of an FMS to some extent, the ROI would be somewhat higher.

A second, worst case, evaluation was also performed, assuming FMS efficiency of only 50%, and stand-alone N/C efficiency of 28.6%, the best client feels they can achieve. Again, from a capacity expansion viewpoint, the FMS was both the lower production cost and smaller investment method. The machine replacement analysis indicated that the ROI from FMS implementation would range from 29% for a ten year part production life to 13% for a five year life.

1.2 RECOMMENDATIONS

The study results demonstrate that client purchase and installation of an FMS for the 53 parts selected can be the most cost-effective approach available. The FMS should include four (4) four-axis horizontal machining centers with the capacity to store at least 90 tools in each automatic tool changer, one (1) vertical turret lathe with automatic tool changer, an inspection robot for process verification, a wire-guided vehicle material handling system, and an automatic storage and retrieval system to store parts and fixtures. The stations in the FMS should be on spur-loops off of the main material handling track to prevent system blocking by stopped carts. Although the FMS was evaluated using Kearney & Trecker and DEA machine characteristics, the recommendation was to issue a Request for Proposal (RFP) to at least three FMS vendors to provide an opportunity for creative solutions to client's production problem.

However, FMS is not necessarily the most risk-free approach to adopt. The degree of system integration and breadth of personnel skills (CNC process planning and programming, software systems, etc.) that must be brought to bear to make an FMS a success in a reasonable time are challenges that will require active and enthusiastic, long-term commitment from all levels of client management and technical personnel, as it does in any organization pursuing an FMS solution to these manufacturing problems.

FMS's are not turnkey systems. Management should not expect that RFQ's can be extended to vendors, one chosen, and the system installed without active continuous involvement by a client FMS team. The nature of FMS is that its production goals undergo frequent changes; client personnel will have to be in control of system operations, CNC programming, process planning in an integrated CNC environment, fixture design (for new parts added to the system from time to time); QC personnel will be continually challenged to exploit the coordinate measuring equipment to the extent possible. The system will have to be carefully specified and implemented to permit some manual operations (particularly during startup and acceptance testing) without loss of data and attendant control and monitoring of system.

FMS's are challenging undertakings with substantial implications for plant management, personnel skills and assignments, long-term commitment, and close client collaboration with system/machine tool vendor. Serious consideration should be given to starting with a series of stand-alone CNC machines, with the capability to be integrated into a full-fledged FMS later, after in-house capabilities have been expanded. Such an approach can be discussed with prospective vendors as part of the RFP reviews for FMS.

2.0 TECHNICAL REVIEW - TEN STEPS FOR FMS DESIGN AND EVALUATION

1. Select candidate parts and machine types.
2. Develop fixturing concepts for each part.
3. Process plan each part.
4. Calculate theoretical number of each type of FMS station.
5. Parts Group (if necessary) and balance the workload across the system.
6. Model the FMS and adjust system size.
7. Simulate the FMS and adjust system size.
8. Perform economic analysis.
9. Evaluate FMS intangibles.
10. If FMS is appropriate, issue an FMS request for proposal.

2.1 STEP 1: SELECT CANDIDATE PARTS AND MACHINE TYPES (PHASE I)

Overview

- In Phase I of the client project, 4,200 parts were analyzed; 4,056 were eliminated based on size, material, processing requirements, end item, etc.

- The 144 remaining parts were matched with 10 FMS machine groups through linear programming to determine what combination(s) of parts and machines were economically justifiable.

- Only small, medium and large machining centers had enough work content to be included economically in an FMS for client.

- To support an FMS with 8 to 10 machines, analysis indicated that at least 40 to 70 parts would be necessary.

- Of those parts chosen as economical candidates for FMS, parts with less than 200 FMS-compatible machining hours annually (based on current client standard times) were eliminated due to their minimal economic benefits, and to reduce the detailed process planning workload. This left 60 parts for review.

- Of the 60 parts reviewed, 8 were eliminated for the following reasons:

  - Would require too many refixturings (greater than 4) to be economical:

    12007790

    6105196

  - Parts were too large for easy FMS handling:

    8433001-365

    8436432

  - Parts had secondary operations only (such as hand drilling):

    12000725

    8449331

- Parts could be produced more efficiently on dedicated equipment:

  11643300 - 5-axis machines, horizontal lathes.

  12007859 - Profiler/tracer machines.

- One part, 8432951, was added due to its common processing requirements to make 53 for detailed process planning.

- Although not indicated as cost effective, VTL's were to be included in the FMS to enable more parts to be machined completely in the FMS.

Phase I Summary

The initial client part set that appeared, from the MICLASS code scan, to have FMS potential contained 243 parts. The customer supplied a tape with the machine code, cost center code, and processing data for these parts plus their computerized process plans and blueprints. This part set consisted of parts for the end-items listed in Figure 1. The entire parts set was first reviewed to see if parts from those end-items listed as unlikely to be produced played a significant role in the FMS justification. All 243 process plans were reviewed and the approximate number of tools required for each part was determined. Most of the parts appeared to require only one relatively simple fixture. However, a quick review of some of the part prints seemed to indicate that a few of the parts would require two fixtures.

Two cases were to be examined, one where all parts required two fixtures, and one where only one fixture apiece was required. We assumed a fixture cost of $10,000 each, a total cost of $75 each for a tool holder and tool, and amortized the sum of the tooling and fixture costs over five years at 18% return on investment. We chose five years as an average part life based on our experience with FMS part sets. Production time was based on a five-day, two-shift week: 240 days annually at 16 hours per day or 3840 annual production hours per machine. FMS would have a production efficiency (i.e., average machine "utilization", or "time in tape") potential of between 70% and 80%. We used 75%, and 80% to examine the sensitivity of FMS justification to the efficiency parameter. We assumed a shop efficiency of 45% for client.

Likely End Items	Unlikely End-Items
M178	M85
	M8C
M174	X198
M140	M101
M102	M39
M45	X1SC
M1	M101A1

Figure 1. Client End-Items Included in FMS Potential Part Data

We estimated the FMS operating cost in the following manner. Currently, client N/C machines have a cost center rate of about $45. Assuming one man per machine ($12.50 per hour), this leaves $32.50 of that rate as overhead resulting from indirect costs attributed to that piece of equipment. The FMS overhead was assumed for simplicity to be equal to the current overhead rate. This is extremely conservative, as overhead usually includes the cost of material handling to and from the machines (which is greatly reduced with an FMS), the cost of rework and scrap (which should also show improvement), supervisory salaries and so on. Two load/unload personnel were assumed to be the maximum necessary for the size range of systems to be reviewed, 4 to 15 machines. In reality, the systems under ten machines for client would probably only require one load person. One supervisor was assumed for both cases, and that cost was ignored. To complete the calculation of FMS operating cost, the hourly rate for the loaders, who usually are machine operators, was divided by the number of machines in the system and added to the hourly rate. Thus, the FMS operating <u>cost ranged from a maximum of $38.75/hour for a four-machine system to a minimum of $34.16/hour for a system with fifteen machines</u>. We used $35/hour based on the fact that the smaller systems should require only one loader (a maximum cost of $35.63/hour). Client cost center data were used to calculate all current operating costs.

Figure 2 on page 14 lists the machine codes determined to process acceptable FMS work content, and divides those codes among ten FMS machine classes. The computerized part routing data were scanned for these codes. Operations having these codes were examined to calculate the current manufacturing cost, the equivalent FMS manufacturing cost, and the cost savings, if any, resulting from processing those operations on an FMS. This cost savings would set equal the current cost less the FMS cost, less the amortized cost of the fixtures and tooling required to produce that part on the FMS. If there were no cost savings for a part, it was rejected from further consideration. Additionally, if the part had to be refixtured more than three times (i.e., it leaves the FMS and returns frequently), it was eliminated due to the difficulty in tracking and controlling production of that part.

<u>192 parts could be produced with savings on the FMS.</u> Both current cost and FMS cost were based on the annual production cycle for the applicable operations and the setup time for that operation. To be conservative, the cycle times for the FMS were set equal to the conventional times. A more realistic value, due to the fact that fixturing the part is done off the machine table and fewer times in an FMS, would be approximately 75% of the current cycle time. Setup is virtually eliminated in the FMS because of dedicated fixtures and preset tooling; however, since one part was assumed to be completed in the setup procedure, the cycle time for one part was added to the FMS time for every setup eliminated. These assumptions are listed in Figure 3 on page 15.

Type	Small	Medium	Large
Machining Center	2010-2040,	2045-2060,	2090-2140,
	2070,	2105,	2185
	2100,2110,	2165-2180,	2188,
	2150-2160,	2190,	2196-2210,
	2270-2290,	2220,	2222-2224,
	2700,	2241-2242,	2245-2261,
	2820,3010,	3020,3030,	2420,2520,
	3040,3050,	3055,	2750,
	3060,3118	3065-3080,	3095,3105
		3100,	3115,
		3112,3113,	3120-3160
		3180-3200	
Precision Boring	2720	2730	2710,2715
			2725
Multi-Spindle		3220,3221,	3230,3250,
		3240	3260
Vertical		2533,	2531,2535,
		2540-2567	2570-2620

Figure 2. FMS-Compatible Client Machine Codes by Appropriate FMS Machine Class

- FMS Cycle Time = 100% of Client Cycle Time. 75% was used in the calculations for Case D to examine the sensitivity of the FMS justification to cycle time.
- One or two fixtures would be required for every part.
- Fixture Cost = $10,000 each.
- Tool Cost = Average $75 each for a tool and holder combination.
- Amortization Period = Average part life of five years.
- Amortization Rate = 18%.
- Available Annual Production Time = 240 days, 2 eight-hour shifts = 3840 hours/year.
- FMS Production Efficiency = Ranges from 70% to 80%, used 75% as an average and 80% for Case C to examine the sensitivity of FMS justification to cycle time.
- Client Shop Efficiency = 45% (average shop efficiency).
- FMS Operating Cost = $35/hour.
- Client Operating Cost = Respective cost center rates.
- System Sizes = Minimum of four machines, maximum of 15 machines.
- System Manning = 1 or 2 load/unload persons, depending on system size.
- One part completed during client setup procedure.
- Setup time is eliminated using the FMS.
- Parts requiring more than three refixturings are not considered for FMS as too difficult to control.

Figure 3. Assumptions

The part cost savings and production time for each FMS machine class was then used by the Draper developed Part and Machine Selection Program (PAMS) to determine the proper selection of parts and machines for various maximum system sizes. After the first run, it was apparent that four machine classes could be eliminated from consideration. Small and medium boring machines were not used by the 192 parts, and medium and large multiple-spindle machines were used so little as to always be uneconomical to include in the FMS. The part savings were recalculated without these groups, and PAMS rerun. No combination of parts could justify vertical turning equipment, nor the large boring machines, so they were eliminated and the part savings recalculated again. It is possible that a piece of turning equipment could be included and justified with extra part savings from the other classes, but we did not investigate that at this time.

This left three machine classes: small, medium and large machining centers. We ran both this combination and just small and medium machining centers, the latter to see if a system with no large machining centers would have a better return on investment (ROI). The small/medium combination did have an ROI a couple of points better, but not a vast improvement overall. Unfortunately, almost all of the parts chosen were for the "unlikely" end-items. We removed all of the parts for these end-items from the dataset, leaving 144 parts total to choose from. Figure 4 on page 17 through Figure 7 on page 20 summarize the results for four combinations of assumptions, from worst case to the best examined, for both the two-machine and three-machine cases. All of the parts are from likely end-items and are listed in Figure 8 on page 21 and keyed to the four summary figures. This last chart might be a bit difficult to follow; it is included so that one can see which parts were chosen when, as well as to show that certain parts were always chosen. The ROIs for the part sets chosen from "likely" end-items are approximately the same as those for the part sets from "unlikely" end-items, so we did not include a summary of the information for the "unlikely" end-items.

These parts are not necessarily machined completely in the FMS; only the work content for those parts that can be performed on the selected FMS machine classes is completed. Additional machining required would be performed more economically using clients's current approaches.

	No. of Machines:		4		5		6		7		8		9
A	Machines in each class:	S	1	0	2	1	2	1	1		2		2
		M	3	3	3	3	4	4	4		6		7
		L		1		1		1	2				
B	Total Investment ($M)		2.665	2.970	2.94	3.255	3.33	3.645	4.245		4.11		4.50
C	No. of Parts with Potential Savings		55	93	55		55	93		93	55	93	55
D	No. of Parts Chosen		9	10	16	18	16	20	16		20		23
E	Annual Savings ($M)		0.692	0.677	0.812	0.839	0.911	0.983	1.118		1.298		1.438
F	Return on Investment (%)		26	23	27.6	25.6	27.4	27	26.3		31.6		32

Chart Key: S = Small machining center.
M = Medium machining center.
L =Large machining center.

In Row A:

- Each column of numbers represents the two-class and three-class cases, respectively.
- A blank indicates that no machines, were chosen or that combination was not investigated.

Nine (9) machines is the maximum size FMS for the two-class case under these conditions.

Seven (7) machines is the maximum for the three-class case.

Figure 4. Summary of Part Selection Results (A): Worst Case Situation: FMS cycle times = current cycle times; 2 fixtures required for every part; FMS eficiency = 75%

	No. of Machines:	4		5		6		7		8		10
A	Machines in each class: S	1	0	2	1	2	1	2	1	2	1	2	2
	M	3	3	3	3	4	4	5	5	6	5	8	5
	L		1		1		1		1		2		3
B	Total Investment ($M)	2.655	2.970	2.94	3.255	3.33	3.645	3.72	4.035	4.11	4.635	4.89	5.52
C	No. of Parts with Potential Savings	82	119	82	119	82	119	82	119	82	119	82	119
D	No. of Parts Chosen	12	10	21	19	24	23	20	30	22	30	32	37
E	Annual Savings ($M)	0.728	0.709	0.926	0.897	1.046	1.052	1.154	1.183	1.366	1.273	1.659	1.675
F	Return on Investment (%)	27.4	23.4	31.5	27.6	31.4	28.9	31	29.3	33	27.5	33.9	30.3

Figure 5. Summary of Part Selection Results (B): FMS cycle times = current cycle times; 1 fixture is required for every part; FMS efficiency = 75%.

		4	5	6
	No. of Machines:	4	5	6
A	Machines in each class: S / M	1 / 3	2 / 3	2 / 4
B	Total Investment ($M)	2.655	2.94	3.33
C	No. of Parts with Potential Savings	86	86	86
D	Chosen No. of parts	12	23	28
E	Annual Savings	0.802	0.974	1.151
F	Return on Investment (%)	30.2	33.1	34.1

Figure 6. Summary of Part Selection Results (C): FMS cycle times = current cycle times; 1 fixture is required for every part; FMS efficiency = 80%. This is done only for the 2-class case to determine how much of an effect system efficiency has on the number of parts selected and ROI.

	No. of Machines:	4		5		6		7		8		9		13
A	Machines in each class: S	1	1	1	1	1	1	1	1	2	1	2	1	2
	M	3	2	4	3	5	3	6	4	6	4	7	4	5
	L		1		1		2		2		3		4	6
B	Total Investment ($M)	2.655	2.97	3.045	3.255	3.435	3.855	3.825	4.245	4.11	4.845	4.50	5.445	7.32
C	No. of Parts with Potential Savings	91	129	91	129	91	129	91	129	91	129	9 1	129	129
D	No. of Parts Chosen	12	24	17	33	20	19	33	33	52	37	72	40	83
E	Annual Savings ($M)	1.181	1.114	1.577	1.457	1.784	1.825	2.014	2.063	2.217	2.369	2.408	2.664	3.55
F	Return on Investment (%)	44.5	37.5	49.8	44.8	52	47.3	52.7	48.6	53.9	48.9	53.5	48.9	48.5

Nine (9) machines is the maximum system size for the two-class case.

Thirteen (13) machines are the maximum for the three-class code.

Figure 7. Summary of Part Selection Results (D): FMS cycle times = 75% of current cycle times; 1 fixture required for each part; FMS efficiency = 80%.

Part No.	Name	End-Item	A 2 Classes					A 3 Classes				B 2 Classes						B 3 Classes						C 2 Classes			D 2 Classes						D 3 Classes						
			4	5	6	8	9	4	5	6	7	4	5	6	7	8	10	4	5	6	7	8	10	4	5	6	4	5	6	7	8	9	4	5	6	7	8	9	11
10884271	Bracket	M140																			•		•								+	+	•	•					•
10888787	Nut	M178							•	•					+				•	•	•		•		•						+	+	•	•					•
10891787	Nut	M178																														+							
10891945	Gear	M174																																					•
10892028	Housing	M174		+	+	+	+		•	•	•		+	+		+	+		•	•	•	•	•		+	+	+		+	+	+	+		•	•	•	•	•	•
10892140	Cover	M174																													+	+		•					•
10892141	Cover	M174																													+	+		•					•
10895603	Follower	M178		+		+									+																+	+		•					•
10895627	Housing	M178																																				•	•
10895673	Housing	M178					+	•		•	•			+			+	•		•	•	•	•						+	+	+	+	•	•	•	•	•	•	•
10895694	Cover	M178																																				•	•
10895695	Sleeve	M178																																			•	•	•
10895696	Sleeve	M178																																				•	•
10909285	Key	M178	+			+	+	•				+	+	+		+	+	•				•		+	+	+	+	+	+	+	+	+				•	•	•	•
10909315	Retainer	M178																														+							
10923025	Lever	M178		+	+	+	+						+	+		+	+					•	•		+	+		+			+	+							•
10923030	Gearshaft	M178											+		+	+			•	•	•	•	•		+						+	+	•	•					•
10930330	Breech	M178	+	+		+	+	•	•	•	•	+	+	+	+	+	+	•	•	•	•	•	•	+	+	+		+	+	+	+	+		•	•	•	•	•	•
10933931	Breech	M178		+	+	+	+		•	•			+	+	+	+	+		•	•	•	•	•		+	+	+	+	+		+	+	•	•	•	•		•	•
10933931	Breech	M178							•	•			+	+	+	+			•	•	•	•	•		+	+		+			+	+		•					•
10933932	Bracket	M140					+			•	•						+			•	•	•	•	+		+			+	+	+	+	•	•	•	•	•	•	•
10934876	Yoke	M174								•																													•
11590764		M1																																				•	•
11636055		M1													+								•								+	+		•					•
11636292	Manifold	M178																																			•	•	•
1164330	Piston	M174																																					•
11E3184	Cap																																						•
12000726	Regulator	M102																				•															•		•
12007602	Cap	M45																														+							•
12007649	Collar	M45							•	•			+		+				•	•	•		•		+	+					+	+		•					•
12007690	Adaptor	M45																												+		+					•	•	•

Figure 8: Number of Machines (Part 1 of 3)

Part No.	Name	End-Item	A: 2 Classes 4 5 6 8 9	A: 3 Classes 4 5 6 7	B: 2 Classes 4 5 6 7 8 10	B: 3 Classes 4 5 6 7 8 10	C: 2 Classes 4 5 6	D: 2 Classes 4 5 6 7 8 9	D: 3 Classes 4 5 6 7 8 9 13
12007692	Cap	M45						+	•
12007719	Yoke	M45							•
12007723	Yoke	M45	+ + + +	•	+ + + + + +	•	+ +	+ + + + + +	• • • • • •
12007721	Body	M45	+ + + +		+ + +			+ + + + + +	
12007765	End	M45							•
12007772	Clamp	M45		•				+ + +	• • • • •
12007782	Nut	M45	+ + + +	• •	+ + + + +	• • • •		+ +	• • •
12007784	Collar	M45			+			+ +	•
12007790	Lever	M45				• •		+ +	• • • • •
12007856	Insert	M45						+ +	• •
12007859	Regulator	M45							•
12007865	Collar	M45						+	
12007872	Housing	M45			+ +	• • •		+ +	• •
12012132	Cover	M178							• •
12274291		M1						+	• • •
12274293		M1			+	•	+	+ + +	• • • •
12274327		M1	+ +	• •		• • • •	+	+ +	• • • • •
12274331		M1	+ + + +	• •	+ + + +	• • • • •	+ +	+ + + + +	• • • • • • •
12282084		M1		• •	+ +	• • • • •		+ + +	• • • • • •
12287139		M1		•		•	+	+	• •
5507255	Guide	M174	+ +	• • •	+ + +	• • • • •	+ +	+ + + +	• • • • • •
5509262	Trunnion	M174						+	•
5509263	Trunnion	M174						+	•
5568984	Head	M174	+ + + +	• •	+ + + + +	• • • •	+ + +	+ + + + + +	• • • • • •
6105141	Nut	M174		• •	+	• •		+ +	• •
6109576	Liner	M174		• • •	+	• • • •		+ + + +	• • • • • •
6507039	Yoke	M174	+ + + + +	• •	+ + + + +	• • • • •	+ + +	+ + + + + +	• • • • • •
6536154	Bdy Req.	M174		•	+ + + +	• • • •	+ +	+ + + + +	• • • • • • •
6505782	Cap	M174	+ + + + +		+ + + + +		+ +	+ + + + +	
6505788	Cap	M174	+ + + +		+ + + + +		+ +	+ +	
7119400	Body	M174						+ +	• • •
7133213	Body	M174						+ +	• •
7133219	Body	M174				•		+ +	• •

Figure 8: Number of Machines (Part 2 of 3)

Part No.	Name	End-Item	A: 2 Classes 4 5 6 8 9	A: 3 Classes 4 5 6 7	B: 2 Classes 4 5 6 7 8 10	B: 3 Classes 4 5 6 7 8 10	C: 2 Classes 4 5 6	D: 2 Classes 4 5 6 7 8 9	D: 3 Classes 4 5 6 7 8 9 1
7119399	Body	M174						+	
8382228	Head	M140						+	
8427051	Box	M174				•		+	•
8427052	Follower	M174							•
8430397	Head	M174	+ + + +	• •	+ + + +	• • • • •	+ +	+ + +	• • • •
8432438	Lever	M162						+	
8432783	Frame	M102		•				+ +	• • •
8432870	Yoke	M102	+ +	•	+ + + +	• • •	+ + +	+ + + + + +	• • • • •
8432874	Body	M102			+ +	• •	+	+ + +	• •
8432887	Yoke	M102	+ + + +	• •	+ + + + +	• • • • •	+ + +	+ + + + + +	• • • • • •
8432888	Yoke	M102	+ + + + +	• • •	+ + + + +	• • • • •	+ +	+ + + +	• • • • • • •
8432951	Housing	M102		•	+ +	• • • •		+ +	• • • • •
8432977	Brocket	M102						+	•
8432978	Hub	M102						+ +	• •
8433001	Subassy	M102							•
8433206	Trail	M102						+ + +	• • •
8433535	Bracket	M102		•		•		+ +	• • • •
8433536	Bracket	M102						+	•
8433578	Housing	M102			+			+	
8433634	Support	M102							• • •
8433635	Support	M102							• • •
8433678	Bracket	M102						+	
8433716	Yoke	M102	+ + +	• • • •	+ + + + +	• • • • • •	+ +	+ + + + + +	• • • • • • •
8433724	Housing	M102			+ +	• • •		+ + +	• • • • •
8433752	Cam	M102				•		+ +	•
8433797	Housing	M102	+ +	• •	+	• • • • •	+	+ + + +	• • • • • • •
8436432	Base	M102							•
8436564	Housing	M102				•		+ +	• • • •
8447496	Housing	M102		• •	+ + +	• • •	+ +	+ + + +	• • •
8449308	Bracket	M140			+			+ + +	• •
8449309	Bracket	M140	+ + + +		+ + + + +		+ +	+ + +	•

Figure 8: Number of Machines (Part 3 of 3)

FMS for Two-Shift Operation:
5 Machining Centers, 2 Turning Machines

Annual Available Shop Hours: 244 x 2 x 8 = 3904 hours/year

At 0.6 availability: 0.6 x 3904 = 2342.4 hours

	Setup	Run	Total
Annual Conventional Machining Center Hours:			
60 vehicles/month	511.5 hrs	27109.8	27,621.3
Annual Conventional Turning Hours:			
60 vehicles/month	173.4 hrs	7653.6	7,827.0

Machining Centers Freed:

60 vehicles/month

At 0.6: 27621.3/2342.4 = 11.79 = 12

Turning Centers Freed:

60 vehicles/month

At 0.6: 7827.0/2342.4 = 3.34 = 4

Figure 9. Typical Machine Replacement Analysis

Table 1. Candidate FMS Parts

No.	Part Number	Name	End Item	Annual Quantity	FMS Compatible Hours	Total Machining Hours	Total Hours
1	10884271	BRACKET	M140	399	206.5	291.1	325.8
2	10891945	GEAR, GUN ELEVATING (MACH)	M174	106	562.6	562.6	1330.2
3	10892028	HOUSING (MACH-CAST)	M174	100	928.8	928.8	1018.7
4	10895603	FOLLOWER FRONT	M178	1134	315.7	1897.0	2458.0
5	10895627	HOUSING (MACH)	M178	599	2639.5	2639.5	2782.7
6	10895673	HOUSING (MACH)	M178	599	1171.9	1321.2	1651.8
7	10895694	COVER (MACHINING)	M178	567	405.8	657.2	976.4
8	10895695	BEARING SLEEVE (MACHINING)	M178	599	1074.9	1693.2	1715.3
9	10895696	BEARING SLEEVE (MACHINING)	M178	599	1062.4	1675.5	1698.4
10	10909285	KEY, TORQUE (MACHINING)	M178	567	1317.4	1317.4	1455.3
11	10922978	BRACKET CAM MOUNTING (MACH)	M178	599	302.2	302.2	346.5
12	10923025	LEVER CAM (MACH)	M178	567	467.6	467.6	628.4
13	10930330	CAM BREECH OPERATING	M178	567	6095.3	6095.3	7964.9
14	10933932	BRACKET	M140	378	820.8	820.8	1041.0
15	11590764		M1	254	512.9	587.6	738.0
16	11636292	MANIFOLD.REPL.SYS	M178	567	1123.9	1123.9	1513.0
17	11643300	PISTON.RECOIL CYLINDER	M174	100	634.9	805.5	1021.2
18	12000725	RECOIL MECHANISM.M37A1	M102	120	228.6	268.6	1854.5
19	12007690	ADAPTOR (MACH)	M45	252	238.6	573.2	638.5
20	12007719	YOKE MIDDLE ASSEMBLY	M45	252	2314.7	2557.0	3190.6
21	12007721	BODY	M45	252	14059.4	18528.7	20298.4
22	12007723	YOKE REAR (MACH)	M45	252	7800.0	10883.6	11809.5
23	12007725	BRACKET (MACH)	M45	252	268.5	280.6	374.4
24	12007765	END	M45	252	445.7	985.2	1141.5
25	12007772	CLAMP (MACH)	M45	756	288.9	288.9	3****7
26	12007790	LEVER	M45	252	270.7	283.3	365.4
27	12007859	REGULATOR	M45	252	1113.8	5633.0	6605.8
28	12012132	COVER TUBING	M178	567	640.3	640.3	843.6
29	12274291		M1	254	1255.4	1646.0	2086.7
30	12274293		M1	254	1508.1	1974.5	2406.8
31	12274327		M1	504	207.4	207.4	297.7
32	12274331		M1	268	406.0	406.0	455.7
33	5507255	GUIDE (MACH)	M174	201	204.7	434.1	560.6
34	5509262	TRUNNION LEFT HAND	M174	106	898.1	898.1	931.7
35	5509263	TRUNNION RIGHT HAND	M174	106	896.0	896.0	929.6
36	5568984	HEAD	M174	201	581.9	1082.0	1200.3
37	6105074	BRACKET	M174	212	263.3	263.3	279.5
38	6105196	LINER	M174	403	279.8	279.8	290.9
39	6505782	CAP TRUNNION LEFT (MACH)	M174	100	1522.2	1869.2	2355.1
40	6505788	CAP TRUNNION RIGHT (MACH)	M174	100	1298.5	1752.6	2210.2
41	6507039	YOKE	M174	100	4461.0	4461.0	4818.3
42	6536154	BODY REGULATOR	M174	100	253.9	924.6	4818.3
43	8430397	HEAD	M174	201	204.3	1110.4	1254.4
44	8432870	YOKE ASSY FRONT (MACHINING)	M102	126	2120.8	2267.5	2536.9
45	8432887	YOKE REAR	M102	126	2891.8	2891.8	3063.4
46	8432888	YOKE CENTER (MACHINING)	M102	126	638.7	759.1	851.0
47	8432977	BRACKET ASSEMBLY	M102	126	209.0	209.0	228.2
48	8433001	SUB ASSY-365 (WELDMENT ONLY)	M102	120	222.3	222.3	1072.0
49	8433535	BRACKET	M102	126	579.7	657.2	748.7
50	8433536	BRACKET RIGHT	M102	126	436.7	507.2	598.2
51	8433634	SUPPORT ASSEMBLY R.H.(MACH)	M102	126	490.6	648.3	889.3
52	8433635	SUPPORT ASSEMBLY L.H.(MACH)	M102	126	532.4	682.2	***.7
53	8433716	YOKE (MACHINING)	M102	126	988.2	988.2	1061.1
54	8433724	HOUSING (MACH)	M102	133	227.1	227.1	259.9
55	8433797	HOUSING.GEAR	M102	252	404.8	428.9	473.6
56	8436432	BASE ASSEMBLY (MACH)	M102	126	756.1	756.1	820.2
57	8447496	HOUSING	M102	133	258.3	708.8	882.1
58	8449308	BRACKET SUPPORT (MACHINING)	M140	378	1951.3	2470.2	30***
59	8449309	BRACKET TORQUE (MACHINING)	M140	378	2870.5	3634.52	4501.8
60	8449331	BUFFER ASSY (COUNTER RECOIL)	M178	540	237.2	237.2	1454.9

2.2 STEP 2: DEVELOP FIXTURE CONCEPTS FOR EACH PART (BEGIN PHASE II)

- All parts were planned for an FMS with four-axis horizontal machining centers and VTL's using 30" or 36" square pallets.
- The system will have only large (30" or 36" square pallet) machining centers, for pallet commonality throughout the system and maximum flexibility. Work for small and medium machining centers can be accomplished on the large machines, but the opposite is not true.
- Fixturing for each part was conceptualized to minimize refixturing to completely machine the part and to provide adequate support for all machining operations.
- Where possible, parts that could possibly share fixtures were considered together.
- These fixturing concepts were reviewed by client process planning personnel and suggested changes were incorporated to assure feasibility.

2.3 STEP 3: PROCESS PLAN EACH PART

- Each of the 53 parts was process-planned in detail based on the fixture concepts developed in Step 2.
- Tooling was standardized as much as possible across all parts.
- Machine parameters for a KT MM800 machining center and a Bullard Dyn-Au-Tape VTL were used as standard.
- Machinability data were taken from the MET-CUT handbook, assuming carbide and coated high speed steel cutters where possible/practical.
- Machinability data were reviewed by client process planning personnel and altered appropriately to reflect practical experience.
- Detailed process plans were reviewed by client personnel and altered appropriately to assure feasibility.
- Process planning summary sheets, machinability data, and machine parameters are included for review in this section.
- Also included in this section are load and unload time estimates for each fixturing of each part, and inspection time estimates.
- Inspection time estimates are for "process verification" only -- inspection of critical features, hole locations, and specific surfaces to maintain machining accuracy. Detailed, "buy-off" inspection could be added to the line, but this is difficult given current state-of-the-art coordinate measuring machines.
- Inspection times are estimated based on the use of a DEA Bravo inspection robot.
- The data tables in Figures 11 through 14 are examples of inputs and outputs of Draper-developed computer aided process plan and cutting tool tabulation program "CTIME".

```
R1  K & T RIA/FMS

  PREC     90   3600.   628.   400.   20.   20.   2.   30   30  K & T 800
  TURN     12    300.  1000.   200.   40.   10.   4.   30   30  VTL
   |        |      |      |      |      |     |     |    |    |
   |        |      |      |      |      |     |     |    |    |__Pallet Shuttle Time Each Way, Seconds
   |        |      |      |      |      |     |     |    |
   |        |      |      |      |      |     |     |    |__Rotary Table Speed, Degrees per Second
   |        |      |      |      |      |     |     |       (not for VTL)
   |        |      |      |      |      |     |     |__Average Tool Positioning Time, Seconds
   |        |      |      |      |      |     |
   |        |      |      |      |      |     |__Tool Change Time, Metal to Metal, Seconds
   |        |      |      |      |      |
   |        |      |      |      |      |__Horse Power
   |        |      |      |      |
   |        |      |      |      |__Maximum Feed Rate, IPM
   |        |      |      |
   |        |      |      |__Maximum Tapping Speed, RPM (Not for VTL)
   |        |      |
   |        |      |__Maximum Spindle Speed, RPM
   |        |
   |        |__Number of Tools in Tool Changer
   |
   |__"PREC" = Machining Center, "TURN" = VTL
```

Figure 10. FMS Machine Parameters

R/MILL	-	Rough Milling
F/MILL	-	Finish Milling
C/MILL	-	Contour Milling
T/MILL	-	Thread Milling
DRILL	-	Drilling
S/DRIL	-	Spade Drilling
M/DRIL	-	METCUT Drilling
G/DRIL	-	Gun Drilling
TREPAN	-	Trepanning
REAM	-	Reaming
TAP	-	Tapping
C/BORE	-	Spot Facing, Counter Boring, Chamfering
WR KEY	-	Woodruff Key Cutting, for Contour Milling Recessed Grooves
S/BORE	-	Semi-Finish Boring
F/BORE	-	Finish Boring
RSP	-	Rough Single Point Turning
FSP	-	Finish Single Point Turning
TSP	-	Single Point Threading

Figure 11. Machinability Data (Part 1 of 3): Tool Codes for Machinability Data

```
=== OUTPUT FROM XPRTUTIL FOR WAL1537 ===

AT 13:53:46 ON 11/29/83 - WAD1677.RIAMDAT.DATA
C
C    THIS DATA SET CONTAINS ALL THE MACHINABILITY DATA FOR ROCK ISLAND
C    ARSENAL. DATA IS ENTERED BY SPECIFIC MATERIAL AND MANUFACTURING
C    PROCESS; FIRST SURFACE SPEED (FEET PER MINUTE), THE FEED PER
C    REVOLUTION OR TOOTH (DEPENDING ON THE TOOL) AND THEN THE METAL'S
C    POWER REQUIREMENT FACTOR. ALL OF THIS DATA IS AVAILABLE FROM
C    THE METCUT HANDBOOK, AND WAS REVIEWED BY FLOOR PERSONNEL.
C
C    FIRST, ENTER THE NUMBER OF MATERIALS CUT, TYPES OF TOOLS USED AND
C    DIFFERENT PART NUMBERS UNDER THE DOTTED LINES PROVIDED
C
C      MA  TL  PARTS
C
        9  18  54
C
C    NEXT, ENTER THE TOOL TYPES USED UNDER THE DOTTED LINES (NO NAME CAN
C    BE LONGER THAN 6 LETTERS
C
C                                TOOLS USED
C
      R/MILL F/MILL C/MILL T/MILL DRILL S/DRIL M/DRIL G/DRIL TREPAN REAM TAP C/BORE WR KEY S/BORE F/BORE RSP FSP TSP
C
C    NEXT, ENTER THE MATERIALS USED DOWN THE LEFT HAND COLUMN AND THE
C    RECOMMENDED SURFACE SPEED IN EACH ROW UNDER THE CORRECT TOOL AND
C    DOTTED LINE. THE MATERIAL NAME CAN HAVE UP TO 5 LETTERS, AND THE
C    SURFACE SPEED CAN HAVE UP TO 6 DIGITS (NO DECIMALS).
C
C MATL                           SURFACE SPEEDS
C
```

MATL	R/MILL	F/MILL	C/MILL	T/MILL	DRILL	S/DRIL	M/DRIL	G/DRIL	TREPAN	REAM	TAP	C/BORE	WR KEY	S/BORE	F/BORE	RSP	FSP	TSP
G120	300	450	235	60	45	40	140	165	300	35	18	55	300	230	345	320	390	150
4130	350	475	275	70	55	30	140	200	300	35	25	60	300	240	385	320	410	150
1020	440	525	350	80	65	55	175	350	350	40	50	75	300	260	490	375	565	150
G105	300	400	235	60	45	40	140	165	300	35	18	55	300	230	345	320	390	150
ALUM	1800	1800	1000	1000	275	600	800	650	500	200	75	750	1500	1800	1800	1800	2000	250
6535	300	400	235	60	45	40	140	165	300	35	18	55	300	230	345	320	390	150
COPPR	600	750	400	300	140	70	300	400	225	80	55	150	440	400	650	500	650	250
BRASS	600	750	400	300	140	70	300	400	225	80	55	150	440	400	650	500	650	250
SS416	265	355	200	70	50	40	140	250	200	35	16	60	300	175	265	245	300	100

```
C
C
C    ADDITIONAL LINES MAY BE INSERTED TO USE UP TO 15 DIFFERENT MATERIALS
C
C    NEXT, ENTER THE MATERIALS USED DOWN THE LEFT HAND COLUMN AND THE
C    RECOMMENDED FEED PER TOOTH OR REVOLUTION (IN THOUSANDTHS OF AN INCH)
C    IN EACH ROW UNDER THE CORRECT TOOL AND DOTTED LINE. THE FEED CAN HAVE
C    UP TO 6 DIGITS (NO DECIMALS).
C
C MATL                           FEED PER REVOLUTION OR TOOTH
C
```

MATL	R/MILL	F/MILL	C/MILL	T/MILL	DRILL	S/DRIL	M/DRIL	G/DRIL	TREPAN	REAM	TAP	C/BORE	WR KEY	S/BORE	F/BORE	RSP	FSP	TSP
G120	8	6	5	1	12	4	8	1	6	8	0	4	16	12	3	15	7	0
4130	8	6	5	1	15	5	8	1	6	8	0	5	16	10	3	15	7	0
1020	10	7	7	1	15	6	8	1	7	12	0	6	16	15	3	15	7	0
G105	8	6	5	1	12	4	8	1	6	8	0	4	16	12	3	15	7	0
ALUM	10	8	6	4	15	4	20	2	3	8	0	8	30	15	6	20	10	0
G105	8	6	5	1	12	4	8	1	6	8	0	4	16	12	3	15	7	0
COPPR	12	8	5	4	16	6	16	2	5	20	0	6	25	15	3	20	7	0

Figure 11. Machinability Data (Part 2 of 3)

```
 BRASS   12    8    5    4   16    6   16    2    5   20    0    6   25   15    3   20    7    0
 SS416    7    5    3    1   12    5    8    1    4    6    0    4   16   12    3   15    7    0
C
C
C
C
C    FINALLY, ENTER THE METAL REMOVAL POWER FACTORS FOR EACH MATERIAL
C    UNDER THE PROPER TOOL AND DOTTED LINE. THESE FACTORS MUST BE
C    DECIMALS (1.3,6.,ETC) AND CAN HAVE UP TO 6 DIGITS TOTAL (INCLUDING
C    THE . ).
C
C MATL                                 POWER FACTORS
C_____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____
  G120  1.5  1.5  1.5  1.5  1.3  1.3  1.3  1.3  1.3   .0   .0   .0  1.4  1.4  1.4  1.4  1.4  1.4
  4130  1.5  1.5  1.5  1.5  1.3  1.3  1.3  1.3  1.3   .0   .0   .0  1.4  1.4  1.4  1.4  1.4  1.4
  1020  1.5  1.5  1.5  1.5  1.3  1.3  1.3  1.3  1.3   .0   .0   .0  1.4  1.4  1.4  1.4  1.4  1.4
  G105  1.5  1.5  1.5  1.5  1.3  1.3  1.3  1.3  1.3   .0   .0   .0  1.4  1.4  1.4  1.4  1.4  1.4
  ALUM  .38  .32  .38  .38  .18  .18  .18  .18  .18   .0   .0   .0  1.4  1.4  1.4  1.4  1.4  1.4
  G105  1.5  1.5  1.5  1.5  1.3  1.3  1.3  1.3  1.3   .0   .0   .0  .28  .28  .28  .28  .28  .28
 COPPR  .60  .55  .60  .60  .25  .25  .25  .25  .25   .0   .0   .0  1.4  1.4  1.4  1.4  1.4  1.4
 BRASS  .60  .55  .60  .60  .25  .25  .25  .25  .25   .0   .0   .0  .55  .55  .55  .55  .55  .55
 SS416  1.5  1.5  1.5  1.5  1.3  1.3  1.3  1.3  1.3   .0   .0   .0  .55  .55  .55  .55  .55  .55
                                                                   1.4  1.4  1.4  1.4  1.4  1.4
C
C
C
C
C    ENTER UNDER THE HEADING SPACE PROVIDED THE QUANTITY OF PART NUMBER
C    PER SHIPSET. THE HEADING DOES NOTHING BUT HELP KEEP TRACK OF THE
C    PART. USE ONLY THE LAST FOUR DIGITS OF EACH PART NUMBER, AND ENTER
C    THEM AS THEY ARE ASSIGNED IN THE CONTROL PROGRAM.
C
C
C ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----
     1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
     1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
     1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
```

Figure 11. Machinability Data (Part 3 of 3)

=== OUTPUT FROM XPRTUTIL FOR WAD1677 ===

AT 10:23:20 ON 11/04/83 - WAD1677.SUMM.DATA(W1)

```
R1    K & T RIA/FMS
PREC  68 3600.  628. 400.  20.  20.   2.  30.  30.
TURN  12  300. 1000. 200.  40.  10.   4.  30.  30.
```

SUMMARY OF PROCESS PLANNING CHART

	CYCLE TIME	DISTRIBUTION OF CYCLE TIME									
		R/MILL	F/MILL	C/MILL	T/MILL	DRILL	S/DRIL	M/DRIL	G/DRIL	TREPAN	REAM
1)PART 10930330	69.51	25.40	6.17	22.55	0.00	3.14	0.00	0.00	0.00	0.00	0.00
2)PART 11590764	21.35	1.69	1.62	3.47	0.00	2.28	0.00	0.00	0.00	0.00	3.02
3)PART 10891945	50.95	10.84	11.90	9.14	0.00	8.34	0.00	0.00	0.00	0.00	0.00
4)PART 10882028	86.08	4.72	5.27	2.28	0.00	12.13	32.32	0.00	0.00	0.00	0.00
5)PART 8432887	114.48	4.63	8.26	13.24	41.96	2.88	0.00	0.00	0.00	0.00	0.00
6)PART 10923025	9.86	0.25	0.29	0.04	0.00	1.11	0.00	0.00	0.00	0.00	2.51
7)PART 8433724	10.57	0.40	0.50	0.00	0.00	1.30	0.00	0.00	0.00	0.00	0.00
8)PART 10933932	27.27	3.14	3.06	5.23	0.00	2.18	0.00	0.00	0.00	0.00	4.30
9)PART 10895627	19.10	0.78	1.88	3.01	0.00	2.34	0.00	0.00	0.00	0.00	0.00
10)PART 10895673	27.53	4.30	4.30	0.00	0.00	5.17	0.00	0.00	0.00	0.00	1.85
11)PART 10895694	6.39	0.97	1.22	0.42	0.00	1.28	0.00	0.00	0.00	0.00	0.00
12)PART 10895695	15.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13)PART 10895696	15.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14)PART 12007723	316.66	50.74	19.79	5.74	39.27	17.23	32.45	0.00	0.00	0.00	0.00
15)PART 12012132	16.12	0.75	0.00	4.47	0.00	3.19	0.00	0.00	0.00	0.00	0.00
16)PART 8432870	127.76	0.89	2.33	2.47	42.60	5.21	0.00	0.00	0.00	0.00	0.00
17)PART 8433535	26.45	0.56	1.70	3.08	0.00	0.84	6.37	0.00	0.00	0.00	0.00
18)PART 8433536	28.91	1.29	2.58	3.08	0.00	1.29	6.37	0.00	0.00	0.00	0.00
19)PART 8433634	29.30	0.95	0.93	0.00	0.00	4.82	0.00	0.00	0.00	0.00	0.00
20)PART 8433635	30.27	0.95	0.93	0.00	0.00	4.82	0.00	0.00	0.00	0.00	0.00
21)PART 8433797	14.98	0.23	0.50	0.00	0.00	1.04	0.00	0.00	0.00	0.00	0.00
22)PART 12274291	59.09	5.14	7.11	7.98	0.00	12.72	0.00	0.00	0.00	0.00	7.83
23)PART 12274293	40.30	4.78	6.64	9.94	0.00	6.87	0.00	0.00	0.00	0.00	2.38
24)PART 12274331	21.13	1.78	0.53	1.73	0.00	2.86	4.91	0.00	0.00	0.00	2.38
25)PART 10895603	22.78	0.00	0.00	0.00	0.00	3.13	2.52	0.00	0.00	0.00	0.00
26)PART 6505782	89.13	15.64	13.87	17.13	0.00	5.33	0.00	0.00	0.00	0.00	0.00
27)PART 6505788	85.30	15.12	13.34	17.13	0.00	3.72	0.00	0.00	0.00	0.00	0.00
28)PART 12007725	14.69	0.78	0.69	0.00	0.00	5.26	0.00	0.00	0.00	0.00	0.00
29)PART 12007765	46.02	0.19	0.00	7.14	0.00	3.46	0.00	0.00	0.00	0.00	0.00
30)PART 8430397	44.34	1.78	0.91	1.75	0.00	1.89	10.91	0.00	3.93	0.00	0.00
31)PART 8432888	33.36	7.42	1.49	0.72	0.00	2.98	0.00	0.00	0.00	0.00	0.00
32)PART 8432951	12.17	0.17	0.20	0.00	0.00	0.97	0.41	0.00	0.00	0.00	0.00
33)PART 8432977	12.01	0.58	0.69	0.19	0.00	0.97	0.00	0.00	0.00	0.00	1.77
34)PART 10922978	2.34	0.61	0.11	0.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35)PART 8433716	26.36	2.93	1.57	2.29	0.00	3.00	0.00	0.00	0.00	0.00	1.98
36)PART 10884271	11.29	1.98	1.47	1.64	0.00	1.00	0.00	0.00	0.00	0.00	0.00
37)PART 12274327	14.84	2.56	2.08	3.33	0.00	1.46	0.00	0.00	0.00	0.00	0.00
38)PART 6105074	26.37	0.00	0.00	5.09	0.00	1.32	0.00	0.52	0.00	0.00	0.00
39)PART 6536154	119.54	0.05	0.00	0.55	35.53	2.08	37.50	0.41	2.99	0.00	0.00
40)PART 6507039	261.81	34.97	1.61	8.55	101.97	0.42	22.76	0.00	0.00	35.11	0.68

Figure 12. Process Planning Summary Example (Part 1 of 2)

41)PART 5507255	52.09	6.53	4.92	2.23	0.00	3.35	0.00	0.00	13.80	0.00	8.16
42)PART 12007721	456.79	87.66	19.26	10.87	103.79	11.94	71.30	0.00	5.66	0.00	35.77
43)PART 11636292	21.12	1.79	1.79	0.39	0.00	6.71	0.00	0.00	0.00	0.00	0.00
44)PART 8447496	20.54	0.08	0.20	0.17	0.00	1.37	0.00	0.00	0.00	0.00	0.00
45)PART 12007690	15.91	1.36	1.31	0.35	0.00	1.49	0.00	0.00	0.00	0.00	2.25
46)PART 12007719	87.28	10.62	8.22	1.45	0.00	9.30	16.04	0.00	0.00	0.00	0.00
47)PART 12007772	4.64	0.12	0.17	0.13	0.00	0.83	0.00	0.00	0.00	0.00	0.00
48)PART 5568984	27.53	0.00	1.48	8.00	0.00	0.83	3.36	0.00	0.00	0.00	1.59
49)PART 5509262	68.27	19.22	8.16	7.69	0.00	5.71	0.00	0.00	0.00	0.00	7.12
50)PART 5509263	68.27	19.22	8.16	7.69	0.00	5.71	0.00	0.00	0.00	0.00	7.12
51)PART 10909285	11.72	0.10	1.08	2.42	0.00	1.25	0.00	0.00	0.00	0.00	0.00
52)PART 8449308	60.19	8.80	10.10	11.17	0.00	13.16	0.00	0.00	0.00	0.00	1.33
53)PART 8449309	61.17	6.51	7.09	7.01	0.00	13.07	0.00	0.00	8.71	0.00	5.15

	CYCLE TIME	DISTRIBUTION OF CYCLE TIME								
		TAP	C/BORE	WR KEY	S/BORE	F/BORE	RSP	FSP	TSP	DEAD
1)PART 10930330.		0.85	1.11	0.00	0.00	0.53	0.00	0.00	0.00	9.77
2)PART 11590764		0.22	1.43	0.00	0.00	0.00	0.00	0.00	0.00	7.63
3)PART 10891945		0.33	3.79	0.00	0.00	0.00	0.00	0.00	0.00	6.63
4)PART 10882028		4.71	3.40	0.34	7.77	2.50	0.00	0.00	0.00	10.63
5)PART 8432887		1.77	1.04	1.05	2.10	4.39	12.11	6.90	0.00	14.17
6)PART 10923025		0.21	0.65	0.00	0.00	0.00	0.00	0.00	0.00	4.80
7)PART 8433724		0.71	0.15	0.07	0.06	0.16	0.00	0.00	0.00	7.23
8)PART 10933932		0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	7.37
9)PART 10895627		1.17	0.47	0.00	0.27	0.73	0.00	0.00	0.00	8.47
10)PART 10895673		1.22	1.05	0.00	0.68	1.91	0.00	0.00	0.00	7.07
11)PART 10895694		0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	2.37
12)PART 10895695		0.00	0.00	0.00	0.00	0.00	5.86	7.58	0.00	1.80
13)PART 10895696		0.00	0.00	0.00	0.00	0.00	5.86	7.58	0.00	1.80
14)PART 12007723		9.93	6.49	3.02	18.49	20.96	30.75	34.35	3.53	23.93
15)PART 12012132		1.32	1.05	0.00	0.00	0.00	0.00	0.00	0.00	5.33
16)PART 8432870		2.65	1.68	15.89	11.86	22.62	0.00	0.00	0.00	19.57
17)PART 8433535		0.06	1.42	0.00	0.86	4.23	0.00	0.00	0.00	7.33
18)PART 8433536		0.35	1.40	0.00	0.86	4.23	0.00	0.00	0.00	7.47
19)PART 8433634		0.00	0.76	0.00	0.00	3.62	4.48	8.00	0.00	5.73
20)PART 8433635		0.00	1.13	0.00	0.00	3.62	4.48	8.00	0.00	6.33
21)PART 8433797		0.75	0.17	0.00	0.25	0.42	0.00	0.00	0.00	11.60
22)PART 12274291		1.44	3.52	0.00	0.00	0.00	0.00	0.00	0.00	13.33
23)PART 12274293		0.66	2.89	0.00	0.00	0.00	0.00	0.00	0.00	6.13
24)PART 12274331		0.49	0.40	0.00	0.32	0.00	0.00	0.00	0.00	5.73
25)PART 10895603		0.75	0.84	0.00	0.00	0.00	4.93	5.54	0.00	5.07
26)PART 6505782		0.87	2.04	0.00	0.00	0.00	12.31	8.03	1.84	12.07
27)PART 6505788		0.39	1.89	0.00	0.00	0.00	12.31	8.03	1.84	11.53
28)PART 12007725		1.73	1.54	0.00	0.10	0.28	0.00	0.00	0.00	4.30
29)PART 12007765		1.56	10.68	1.09	0.00	0.09	5.83	3.59	2.00	10.40
30)PART 8430397		0.85	0.34	0.14	0.44	1.39	6.60	2.10	0.15	11.17
31)PART 8432888		2.04	1.24	0.00	3.11	8.33	0.00	0.00	0.00	6.03
32)PART 8432951		0.84	0.09	0.03	0.19	0.33	0.00	0.00	0.00	8.93
33)PART 8432977		0.29	0.19	0.00	0.00	0.00	0.00	0.00	0.00	7.33
34)PART 10922978		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
35)PART 8433716		1.47	1.99	0.00	1.33	2.78	0.00	0.00	0.00	7.00
36)PART 10884271		0.32	0.91	0.00	0.00	0.00	0.00	0.00	0.00	3.97
37)PART 12274327		0.00	2.88	0.00	0.00	0.00	0.00	0.00	0.00	2.53
38)PART 6105074		0.00	2.11	0.00	0.00	0.00	7.33	6.55	0.00	3.43
39)PART 6536154		0.22	0.68	0.00	0.00	0.00	15.09	11.12	0.00	13.33

Figure 12. Process Planning Summary Example (Part 2 of 2)

```
=== OUTPUT FROM XPRTUTIL FOR WAD1677 ===

AT 09:40:12 ON 12/02/83 - WAD1677.WTOOL.LIST

        TOOLS REQUIRED FOR THIS SHIPSET

PART NUMBER  PART 10930330     REQUIRES THE FOLLOWING TOOLS

   TOOL TYPE   DIAMETER   # OF TEETH    TOOL #

     R/MILL     6.0000         8           1
     F/MILL     6.0000         8           2
     C/MILL     2.0000         4           3
     R/MILL     2.0000         4           4
     F/MILL     2.0000         4           5
     C/BORE     0.2600         1           6
     DRILL      0.8050         1           7
     C/BORE     0.9250         1           8
     TAP        0.8750        14           9
     DRILL      0.8594         1          10
     F/BORE     0.8755         1          11
     DRILL      0.2130         1          12
     TAP        0.2500        20          13
     C/BORE     0.7800         1          14
     DRILL      0.7344         1          15
     F/BORE     0.7505         1          16
     R/MILL     1.2500         3          17
     F/MILL     1.2500         3          18
     R/MILL     0.5000         4          19
     F/MILL     0.5000         4          20
     C/MILL     1.2500         3          21
     C/MILL     1.2600         4          22
     F/MILL     1.2600         4          23
     R/MILL     1.2600         4          24
     DRILL      0.2500         1          25
     C/MILL     0.7500         4          26
     F/MILL     3.0000         6          27

  27  TOOLS ARE REQUIRED TO MACHINE THIS PART

PART NUMBER  PART 11590764     REQUIRES THE FOLLOWING TOOLS

   TOOL TYPE   DIAMETER   # OF TEETH    TOOL #

     R/MILL     4.0000         6          28
     F/MILL     4.0000         6          29
     C/MILL     2.0000         4           3
     F/MILL     2.0000         4           5
     C/MILL     0.5000         4          30
     F/MILL     0.5000         4          20
     C/BORE     0.2600         1           6
     DRILL      0.5000         1          31
     DRILL      0.5469         1          32
     DRILL      0.7500         1          33
     C/BORE     1.2500         1          34
     DRILL      0.7344         1          15
     REAM       0.7500         1          35
     C/BORE     0.9000         1          36
```

Figure 13. Unique-Tool List for Each Client Part Example (Part 1 of 2)

C/BORE	0.3800	1	37
DRILL	0.3320	1	38
C/BORE	1.0000	1	39
TAP	0.3750	24	40
C/BORE	0.7500	1	41

19 TOOLS ARE REQUIRED TO MACHINE THIS PART

PART NUMBER PART 10891945 REQUIRES THE FOLLOWING TOOLS

TOOL TYPE	DIAMETER	# OF TEETH	TOOL #
R/MILL	4.0000	6	28
F/MILL	4.0000	6	29
C/BORE	1.2500	1	34
DRILL	1.5600	1	42
C/BORE	2.7500	1	43
C/MILL	2.0000	4	3
F/MILL	2.0000	4	5
C/MILL	1.0000	4	44
F/MILL	1.0000	4	45
C/BORE	0.2600	1	6
DRILL	1.3100	1	46
DRILL	1.0600	1	47
C/BORE	2.0000	1	48
C/BORE	2.5000	1	49
DRILL	0.4531	1	50
TAP	0.5000	20	51
R/MILL	2.0000	3	52
F/MILL	2.0000	3	53
DRILL	0.8800	1	54

19 TOOLS ARE REQUIRED TO MACHINE THIS PART

PART NUMBER PART 10882028 REQUIRES THE FOLLOWING TOOLS

TOOL TYPE	DIAMETER	# OF TEETH	TOOL #
R/MILL	4.0000	6	28
F/MILL	4.0000	6	29
S/DRIL	2.1250	1	55
S/BORE	2.2500	1	56
S/BORE	2.4000	1	57
S/BORE	2.5500	1	58
S/BORE	2.7500	1	59
S/BORE	2.9300	1	60
F/BORE	2.9520	1	61
S/BORE	2.8100	1	62
F/BORE	2.8340	1	63
WR KEY	1.0000	1	64
C/BORE	0.2600	1	6
DRILL	0.2130	1	12
TAP	0.2500	28	65
DRILL	0.4844	1	66
DRILL	0.5625	1	67
C/BORE	1.0000	1	39
DRILL	0.6250	1	68
C/MILL	0.5000	4	30

Figure 13. Unique-Tool List for Each Client Part Example (Part 2 of 2)

=== OUTPUT FROM XPRTUTIL FOR WAD1677 ===

AT 09:40:23 ON 12/02/83 - WAD1677.WUTOL.LIST

TOOLS REQUIRED FOR THIS SHIPSET

TOOL TYPE	DIAMETER	# OF TEETH	TOOL #
R/MILL	6.0000	8	1
F/MILL	6.0000	8	2
C/MILL	2.0000	4	3
R/MILL	2.0000	4	4
F/MILL	2.0000	4	5
C/BORE	0.2600	1	6
DRILL	0.8050	1	7
C/BORE	0.9250	1	8
TAP	0.8750	14	9
DRILL	0.8594	1	10
F/BORE	0.8755	1	11
DRILL	0.2130	1	12
TAP	0.2500	20	13
C/BORE	0.7800	1	14
DRILL	0.7344	1	15
F/BORE	0.7505	1	16
R/MILL	1.2500	3	17
F/MILL	1.2500	3	18
R/MILL	0.5000	4	19
F/MILL	0.5000	4	20
C/MILL	1.2500	3	21
C/MILL	1.2600	4	22
F/MILL	1.2600	4	23
R/MILL	1.2600	4	24
DRILL	0.2500	1	25
C/MILL	0.7500	4	26
F/MILL	3.0000	6	27
R/MILL	4.0000	6	28
F/MILL	4.0000	6	29
C/MILL	0.5000	4	30
DRILL	0.5000	1	31
DRILL	0.5469	1	32
DRILL	0.7500	1	33
C/BORE	1.2500	1	34
REAM	0.7500	1	35
C/BORE	0.9000	1	36
C/BORE	0.3800	1	37
DRILL	0.3320	1	38
C/BORE	1.0000	1	39
TAP	0.3750	24	40
C/BORE	0.7500	1	41
DRILL	1.5600	1	42
C/BORE	2.7500	1	43
C/MILL	1.0000	4	44
F/MILL	1.0000	4	45
DRILL	1.3100	1	46
DRILL	1.0600	1	47
C/BORE	2.0000	1	48
C/BORE	2.5000	1	49
DRILL	0.4531	1	50
TAP	0.5000	20	51
R/MILL	2.0000	3	52

Figure 14. Total FMS Unique-Tool List Example

Table 2. Part Load/Unload Times (Min.), Per Fixturing Example

Part No.	Fixture	Load	Unload
10884271	1	8	2
	2	8	2
10891945	1	8	5
	2	5	5
10892028	1	10	2
10895603	1	5	3
	2	5	3
10895627	1	8	2
10895673	1	3	1
	2	2	1
10895694	1	8	2
10895695	1	5	3
	2	5	3
10895696	1	5	3
	2	5	3
10909285	1	8	4
	2	8	4
10922978	1	5	1
10923025	1	2	1
10930330	1	10	5
	2	10	5
10933932	1	5	2
	2	5	2
11590764	1	3	1
	2	3	1
11636292	1	2	1
	2	2	1
12007690	1	3	1
12007719	1	8	5
	2	10	5
12007721	1	8	5
	2	10	5
	3	10	5
12007723	1	10	5
	2	15	5
12007725	1	2	1
12007765	1	3	2
	2	4	2
	3	2	2
12007772	1	10	5
12012132	1	2	1
	2	3	1

Table 3. DEA Coordinate Measuring Machine Parameters (Seconds)

	Bravo Robot	Gantry
Time to Establish Reference Axes	120	240
Time to Check Parallel/Perpendicular Surfaces	7	12
Time to Check Hole Diameter/Establish Hole Axis Location:		
Hole Diameter < 6"	6	10
Hole Diameter > 6"	6	10
Time to Check Surface Flatness	3	5
Time to Measure from Surface to Surface	3	5
Time to Check Outside Diameter	6	10
Movement Time - 8"-10"	2.5	4.5
Time to Calculate True Position:		
Hole to Surface	Done Simultaneously with Other Measurements	
Hole to Hole		

DEA Bravo Robot chosen as standard for inspection calculations.

Table 4. Inspection Time Estimates

Part No.	Establish Reference Axes	Parallel/ Perpendicular Surfaces	Diameter/Axis True Position		Surface/ Surface/ Flatness	Outside Diameter	Move Time	Total Time
			Holes < 6"	Holes > 6"				
	Seconds	# Feat./Sec.	# Feat./Sec.	# Feat./Sec.	# Feat./Sec.	# Feat./Sec.	Seconds	Sec./Min.
10884271	120	2/14	2/12	0	0	0	10	156/2.60
10891945	120	6/42	4/24	0	5/15	0	38	239/3.98
10892028	120	2/14	10/60	0	0	0	30	224/3.73
10895603	120	1/1	9/54	0	0	4/24	35	240/4.0
10895627	120	1/1	22/132	3/18	0	1/6	67.5	350.5/5.8
10895673	120	0	21/126	0	0	0	52.5	298.5/4.9
10895694	120	0	10/60	1/6	10/30	0	52.5	268.5/4.4
10895695	120	0	0	1/6	0	1/6	5	137/2.28
10895696	120	0	0	1/6	0	1/6	5	137/2.28
10909285	120	3/21	10/60	0	0	0	32.5	233.5/3.8
10922978	120	0	0	1/6	1/3	0	5	134/2.23
10923025	120	1/7	3/18	0	0	0	10	155/2.58
10930330	120	2/14	3/18	0	5/15	0	25	192/3.2
10933932	120	0	5/30	0	2/6	0	17.5	173.5/2.8
11590764	120	2/14	3/18	0	0	0	12.5	164.5/2.7
11636292	120	0	10/60	0	1/3	0	27.5	210.5/3.5
12007690	120	4/28	3/18	0	0	0	17.5	183.5/3.0
12007719	120	5/35	17/102	2/12	1/3	0	62.5	334.5/5.5
12007721	120	5/35	20/120	2/12	6/18	0	82.5	387.5/6.4
12007723	120	6/42	25/150	3/18	7/21	0	102.5	453.5/7.5
12007725	120	0	6/36	0	2/6	0	20	182/3.03
12007765	120	0	4/24	0	1/3	3/18	20	185/3.06
12007772	120	0	3/18	0	0	0	7.5	145.5/2.4
12012132	120	1/7	6/36	2/12	0	0	22.5	197.5/3.2
12274291	120	3/21	19/114	0	3/9	0	62.5	326.5/5.4
12274293	120	4/28	11/66	0	0	0	37.5	253.5/4.2
12274327	120	0	4/24	0	1/3	0	12.5	159.5/2.6
12274331	120	1/7	4/24	0	1/3	0	20	174/2.90
5507255	120	0	10/60	0	2/6	0	30	216/3.60
5509262	120	0	2/12	0	0	1/6	7.5	145.5/2.4
5509263	120	0	2/12	0	0	1/6	7.5	145.5/2.4
5568984	120	2/14	2/12	2/12	0	0	15	173/2.88
6105074	120	0	0	0	1/3	2/12	7.5	142.5/2.3
6505782	120	0	10/60	4/24	1/3	1/8	45	260/4.33
6505788	120	0	10/60	4/24	1/3	1/8	45	260/4.33
6507039	120	0	10/60	4/24	2/6	0	40	266/4.43
6536154	120	0	12/72	0	0	6/36	45	273/4.55
8430397	120	0	5/30	0	0	5/30	25	205/3.42
8432870	120	4/28	16/96	2/12	1/3	0	57.5	316.5/5.2
8432887	120	6/42	8/48	4/24	1/3	0	47.5	284.5/4.7
8432888	120	5/35	6/36	1/6	0	0	30	227/3.78
8432977	120	2/14	11/66	0	4/12	0	42.5	254.5/4.2
8433535	120	3/21	8/48	0	0	0	27.5	216.5/3.6
8433536	120	3/21	8/48	0	0	0	27.5	216.5/3.6
8433634	120	0	10/60	0	1/3	4/24	37.5	244.5/4.0
8433635	120	0	10/60	0	1/3	4/24	37.5	244.5/4.0
8433716	120	3/21	6/36	0	1/3	0	25	205/3.42
8443724	120	0	24/144	0	0	0	60	324/5.40
8433739	120	3/21	19/114	0	3/9	0	62.5	326.5/5.4
8447496	120	7/35	20/120	4/24	0	2/12	77.5	388.5/6.4
8449308	120	7/35	15/90	0	0	0	50	295/4.92
8449309	120	7/35	18/120	0	2/6	0	62.5	331.5/5.5
8432951	120	0	14/84	0	2/6	0	40	250/4.17

2.4 STEP 4: CALCULATE THEORETICAL NUMBER OF EACH TYPE OF FMS STATION

- Available time, annually: 240 days, two 8-hour shifts.

  240 x 2 x 8 = 3,840 hours

- Assumed FMS efficiency/utilization: 75%.

- 25% cushion includes machine/material handling system/computer downtime (unexpected and P.M.), scheduling gaps for raw material, broken tools, etc.

- FMS production time available annually:

  3,840 hours x 0.75 = 2,880 hours

- Total horizontal machining center hours required: 9,678.60 hours.

  Number of horizontal machining centers needed at 75% utilization:

  9,678.60/2,880.0 = 3.36 = 4 machines

  Sensitivity:

Assumed Utilization	Number of Machining Centers
50%	5.04 = 6
60%	4.20 = 5
65%	3.90 = 4
70%	3.60 = 4
75%	3.40 = 4
80%	3.20 = 4
85%	2.97 = 3
100%	2.52 = 3

- Total vertical turret lathe hours required: 1,817.7 hours.

  Number of VTL's needed at 75% utilization:

  1,817.7/2,880 = 0.63 = 1 machine

  Sensitivity:

Assumed Utilization	Number of VTL's
60%	0.8 = 1
75%	0.6 = 1
100%	0.5 = 1

- Total load/unload hours required: 4,164.8

  Number of load/unload stations needed at 75% utilization:

  $$4{,}164.8/2{,}880.0 = 1.45 = 2$$

  Sensitivity:

Assumed Utilization	Number of Load/Unload Stations
60%	1.8 = 2
75%	1.5 = 2
100%	1.1 = 2

- Total inspection hours required:

Inspect every part	- 1,299.8
Inspect every fifth part	- 260.0
Inspect every tenth part	- 130.0

  Number of inspection stations needed for 75% utilization:

  $$1{,}299.8/2{,}880.0 = 0.45 = 1$$

  Sensitivity:

Assumed Utilization	Number of Inspection Stations
60%	0.56 = 1
75%	0.45 = 1
100%	0.34 = 1

- One inspection robot appears adequate to perform "process-verification" inspection on every part produced by the system.

2.5 STEP 5: GROUP PARTS AND BALANCE THE WORKLOAD ACROSS THE SYSTEM

- Parts grouping and balancing of the workload need only be considered for the four horizontal machining centers; after parts grouping (if necessary), the load/unload station work content for each parts group will be balanced between the two load/unload stations manually. Since there are only one VTL and one inspection robot required in the system, their impact on the parts grouping and work load balancing procedure will be examined in Step 6, System Modeling.

- There are 2,880 hours (172,800 minutes) available annually to operate the system at 75% efficiency.

- Several tool chain sizes per machine were examined to investigate the sensitivity of the problem to on-machine tool storage. A summary of the results of these trials is included for review in this section.

- No reasonable tool chain size will allow placement of all of the work content into a single parts group.

- The recommended parts grouping/balancing strategy is to have 90-tool chains on each of the four machines. This allows all of the work to be processed by the FMS using just two parts groups and 152,855.18 minutes (theoretically). The part/machine and tool/machine assignments are included for review in this section.

- The use of very large tool chains (136) on each machine would allow all of the work to be assigned to just three machines using two parts groups. However, the total time to produce those two parts groups exceeds the total time available at 75% utilization. Better than 85% utilization would have to be assumed to allow three machining centers to complete the workload. Experience with operating FMS's indicates that this is too optimistic an assumption.

Table 5. Parts Grouping Strategies Based on Tool Magazine Capacities

Tool Chain Size	Number of Machines	Number of Parts Groups	Production Time Required (Minutes)
68	4	3	156,962.88
90	4	2	152,855.16
110	4	2	150,378.63
136	4	2	150,556.63
136	3	2	202,434.56

Production Time Available at 75% Utilization: 172,800 minutes
Production Time Available at 85% Utilization: 195,840 minutes

Table 6. Part/Machine/Tool Assignments for Parts Group 1 (Part 1 of 2)

MACHINE ASSIGNMENT LIST

MACHINE# 1

PART#	SEGMENT#	REDUNDANCY	CYCLE TIME
7721	2	1	67137.81
7039	2	1	15615.00
2028	1	1	8818.00
5673	1	1	6750.73
5782	2	1	3666.00
7039	1	1	3044.00
3797	2	1	2275.56

TOTAL CYCLE TIME 107306.87

TOTAL NO.OF TOOLS 83

TOOLS REQUIRED ON MACHINE# 1

1	3	6	12	13	20
21	28	30	31	38	39
40	44	50	51	52	55
56	57	58	59	60	61
62	63	64	65	66	67
68	69	125	126	134	135
136	170	174	182	183	192
224	232	256	267	268	269
270	271	272	273	276	331
337	482	483	484	485	486
487	488	489	490	491	492
493	494	518	520	521	522
523	524	525	526	527	528
529	530	531	532	533	

MACHINE# 2

PART#	SEGMENT#	REDUNDANCY	CYCLE TIME
7721	1	1	45433.08
7723	1	1	17844.12
6292	1	1	11425.04
7719	1	1	8961.12
5603	1	1	8414.28
9308	2	1	6531.84
5788	2	1	3379.00
5782	1	1	3039.00
5788	1	1	2943.00
6292	2	1	1967.49

TOTAL CYCLE TIME 109937.56

TOTAL NO.OF TOOLS 78

TOOLS REQUIRED ON MACHINE# 2

1	3	6	13	20	26
28	30	31	32	44	57
64	67	73	74	75	76
121	126	150	152	153	155
156	157	158	158	159	160
161	162	163	174	201	205
206	208	230	273	279	312
313	314	315	316	317	319
320	321	331	332	358	382
403	502	503	504	505	506
507	508	509	510	511	512
513	514	534	535	536	537
538	539	540	541	542	571

Table 6. Part/Machine/Tool Assignments for Parts Group 1 (Part 2 of 2)

MACHINE# 3

PART#	SEGMENT#	REDUNDANCY	CYCLE TIME
7723	2	1	44704.80
9308	1	1	17270.82
7719	2	1	12285.00
5673	2	1	11027.59
4291	1	1	8140.70
5694	1	1	4246.83
9285	2	1	3480.19
3797	1	1	2265.48

TOTAL CYCLE TIME 103421.25

TOTAL NO.OF TOOLS 88

TOOLS REQUIRED ON MACHINE# 3

5	6	12	13	20	26
28	30	32	34	37	41
50	51	64	65	68	82
107	116	137	138	139	140
141	142	143	144	164	165
166	167	168	169	170	171
172	174	175	176	177	178
179	180	181	182	183	184
185	186	187	189	190	191
192	196	230	255	256	257
258	259	260	261	262	263
264	265	266	274	276	277
279	280	281	282	283	288
443	574	575	596	597	598
599	600	601	602		

MACHINE# 4

PART#	SEGMENT#	REDUNDANCY	CYCLE TIME
9309	1	1	23727.06
0330	2	1	22192.38
0330	1	1	18620.28
5627	1	1	12159.70
4293	1	1	10647.68
4291	2	1	7576.82
9285	1	1	4953.73
3536	1	1	3793.86
3535	1	1	3471.30

TOTAL CYCLE TIME 107142.56

TOTAL NO.OF TOOLS 86

TOOLS REQUIRED ON MACHINE# 4

1	2	3	6	7	8
9	10	11	12	13	14
15	16	17	19	21	22
25	26	27	28	30	31
32	34	35	37	39	44
48	50	51	65	67	69
73	82	121	122	123	124
125	126	127	128	129	130
131	132	133	144	165	174
188	219	220	223	224	225
226	227	228	229	230	231
232	233	234	235	236	237
280	283	284	285	286	288
290	291	293	571	603	605
606	607				

PARTS GROUP #1 SUMMARY

MACH#	TOTAL TIME	TOTAL TOOLS
1	107306.875	83
2	109937.562	78
3	103421.250	88
4	107142.562	86

AVERAGE MACHINE UTILIZATION	AVERAGE TOOL UTILIZATION	TOTAL NUMBER OF TOOLS
0.973	0.931	335

Table 7. Part/Machine/Tool Assignments for Parts Group 2 (Part 1 of 2)

MACHINE ASSIGNMENT LIST

MACHINE# 1

PART#	SEGMENT#	REDUNDANCY	CYCLE TIME
2870	2	1	12239.64
7690	1	1	4425.12
6154	2	1	4274.00
4331	1	1	3647.48
2870	1	1	3150.00
9262	2	1	2841.86
0397	2	1	2610.99
9263	1	1	2553.54
0764	2	1	2240.28
2888	1	1	1729.98
2871	1	1	1194.48
5074	1	1	655.08
7496	2	1	529.34

TOTAL CYCLE TIME 42091.77

TOTAL NO.OF TOOLS 80

TOOLS REQUIRED ON MACHINE# 1

1	3	13	15	20	25
26	28	30	35	41	44
52	54	73	74	75	82
100	101	122	123	134	174
182	183	188	197	198	199
200	201	202	203	204	205
206	207	208	209	210	211
212	213	214	215	216	217
218	219	220	221	222	263
273	283	288	292	293	353
379	380	381	382	383	384
385	463	464	465	466	467
468	565	566	567	569	570
594	595				

MACHINE# 2

PART#	SEGMENT#	REDUNDANCY	CYCLE TIME
2887	2	1	9444.96
3025	1	1	6271.02
7772	1	1	4301.64
1945	1	1	4193.66
3716	1	1	3272.22
4271	1	1	3100.23
2887	1	1	2773.26
5074	2	1	2302.32
2978	1	1	2030.61
4327	2	1	1748.88
1945	2	1	1424.64
7496	1	1	1117.20

TOTAL CYCLE TIME 41985.61

TOTAL NO.OF TOOLS 83

TOOLS REQUIRED ON MACHINE# 2

3	6	13	15	19	20
26	28	30	33	34	42
43	44	46	47	48	49
50	51	52	54	64	70
72	73	74	75	76	77
78	80	82	83	84	85
86	87	88	89	90	91
92	93	94	95	96	97
98	99	100	101	102	103
105	120	122	123	174	196
220	273	276	290	312	313
319	354	406	407	408	409
410	411	418	419	561	562
563	564	577	578	579	

Table 7. Part/Machine/Tool Assignments for Parts Group 2 (Part 2 of 2)

MACHINE# 3

PART#	SEGMENT#	REDUNDANCY	CYCLE TIME
7255	2	1	8423.91
2132	2	1	6327.72
7765	1	1	5853.96
3932	2	1	4176.90
√0397	1	1	3209.97
9263	2	1	2841.86
4331	2	1	2698.76
9262	1	1	2553.54
4271	2	1	2210.46
2951	1	1	1745.00
3724	1	1	1630.58
6154	1	1	723.00
3716	2	1	419.58

TOTAL CYCLE TIME 42815.21

TOTAL NO.OF TOOLS 78

TOOLS REQUIRED ON MACHINE# 3

3	6	13	20	26	28
30	32	35	37	38	40
41	44	50	51	52	64
82	106	107	108	109	110
111	112	113	114	115	116
117	119	120	121	165	174
193	196	197	225	227	230
251	265	273	283	295	296
315	333	352	353	354	355
356	357	358	359	377	378
390	391	392	393	394	395
412	440	441	442	443	497
498	499	500	501	594	595

MACHINE# 4

PART#	SEGMENT#	REDUNDANCY	CYCLE TIME
3932	1	1	7238.70
4327	1	1	6839.28
8984	1	1	4321.50
2132	1	1	4258.17
7725	1	1	4009.32
0764	1	1	3754.12
2888	2	1	2831.22
7255	1	1	2568.78
2951	2	1	1857.50
3635	1	1	1823.22
2977	1	1	1714.86
3634	1	1	1701.00

TOTAL CYCLE TIME 42917.65

TOTAL NO.OF TOOLS 73

TOOLS REQUIRED ON MACHINE# 4

1	3	6	15	25	28
30	31	32	33	34	35
36	37	38	39	40	44
50	51	52	64	68	106
109	110	118	150	165	177
180	192	193	195	197	200
201	211	220	225	250	251
252	253	254	263	273	305
315	333	334	335	336	337
386	387	388	389	396	397
398	399	400	401	402	404
405	413	495	585	586	587
588					

PARTS GROUP #2 SUMMARY

MACH#	TOTAL TIME	TOTAL TOOLS
1	42091.766	80
2	41985.613	83
3	42815.215	78
4	42917.648	73

AVERAGE MACHINE UTILIZATION	AVERAGE TOOL UTILIZATION	TOTAL NUMBER OF TOOLS
0.989	0.872	314

2.6 STEP 6: MODEL THE FMS AND ADJUST SYSTEM SIZE

- Modeling is basically rough-cut simulation, allowing the system designer to quickly and inexpensively analyze the operating characteristics of the FMS as designed. Problem areas and bottlenecks can be determined rapidly and numerous solutions tested before using simulation to provide the final analysis of system operating characteristics.

- The modeling used here is based on "Network of Queues" theory. We developed and used a software package called MVAQ (Mean Value Analysis of Queues) which is similar in technique to the commercially available queuing model package, CANQ. Production rates and time in system for each part type is calculated by MVAQ.

- MVAQ and CANQ provide conservative estimates of FMS production capability because both packages implicitly assume exponential service times for each part based on the part's tape time instead of simply using the tape time.

- Given part cycle times, required production rates, number of carts desired and maximum number of parts allowable in the system at one time, MVAQ will model the performance of the FMS for each parts group and part/machine allocation generated in Step 5. MVAQ calculates system performance measures, such as part production rate, station utilization, and cart utilization. Iterative runs of the problem allow the user to estimate the optimum number of parts, fixtures and carts in the system, as well as eliminate potential bottlenecks in the system. When the user is satisfied with the FMS design, that one design can be simulated in detail (see Step 7) without the expense and time usually wasted on eliminating non-optimum designs.

- The results of the MVAQ analyses of the client FMS design are included for review in this section.

- MVAQ analysis indicated that the optimum FMS design would consist of:

	MVAQ Station
4 Machining Centers	1, 2, 3, 4
1 VTL	8
1 Inspection Robot	7
2 Load/Unload Stations	5, 6
2 Carts	9
19 Parts in System Maximum	

- Fixtures with more than one part will have only the first and last part inspected per fixturing (i.e., two parts per fixture trip into the FMS). This maintains a more even load on the single inspection machine, and reduces the potential for bottlenecking at this station. Additionally, we chose to reduce the inspection frequency of Part Number 10895603 to 50% (inspect one for every two produced) to reduce the load on the inspection robot.

- Production levels indicated by MVAQ as obtainable by the FMS with two carts are summarized by part number in Table 11, Step 7. Required production rates could be achieved within the time allowed for 75% utilization of the system.

Table 8. MVAQ Results for Parts Group 1, Machines with 90 Tool Storage

Max. Parts in System	10	15	19	20	21	25
Carts in System	2	2	2	2	2	2
Parts Per Hour	3.05	3.51	3.73	3.77	3.81	3.94
Station Utilization (%)						
1	66.53	76.57	81.41	82.36	83.22	86.0
2	68.36	78.67	83.65	84.62	85.50	88.36
3	63.97	73.62	78.28	79.19	80.01	82.69
4	66.48	76.51	81.35	82.30	83.16	85.94
5	48.85	56.22	59.78	60.47	61.10	63.15
6	40.84	47.00	49.97	50.55	51.08	52.79
7	27.39	31.00	33.51	33.90	34.25	35.40
8	48.66	56.01	59.55	60.24	60.87	62.91
9	34.65	39.88	42.40	42.89	43.34	44.79

Table 9. MVAQ Results for Parts Group 2, Machines with 90 Tool Storage

Max. Parts in System	10	15	19	20	21	25
Carts in System	2	2	2	2	2	2
Parts Per Hour	5.38	6.32	6.80	6.90	6.99	7.29
Station Utilization (%)						
1	59.93	70.34	75.72	76.80	77.81	81.16
2	60.05	70.48	75.87	76.96	77.96	81.32
3	59.82	70.21	75.58	76.67	77.67	81.01
4	59.77	70.15	75.52	76.60	77.60	80.94
5	56.37	66.16	71.22	72.24	73.19	76.34
6	43.48	51.04	54.94	55.73	56.46	58.89
7	35.88	42.02	45.24	45.88	46.48	48.49
8	50.77	59.58	64.14	65.06	65.91	68.75
9	56.91	66.79	71.90	72.93	73.89	77.07

Table 10. Sensitivity to Number of Carts in System

	Parts Group 1			Parts Group 2		
Parts in System	19	19	19	19	19	19
Carts in System	1	2	3	1	2	3
Parts Per Hour	3.57	3.73	3.74	4.71	6.80	6.94
Station Utilization (%)						
1	77.95	81.41	81.59	52.49	75.72	77.26
2	80.09	83.65	83.83	52.59	75.87	77.41
3	74.95	78.28	78.45	52.39	75.58	77.12
4	77.89	81.35	81.53	52.35	75.52	77.06
5	57.24	59.78	59.91	49.37	71.22	72.67
6	47.85	49.97	50.08	38.08	54.94	56.06
7	32.09	33.51	33.59	31.36	45.24	46.16
8	57.02	59.55	59.68	44.46	64.14	65.45
9	81.19	42.40	28.33	99.68	71.90	48.91

2.7 STEP 7: SIMULATE THE FMS AND ADJUST SYSTEM SIZE

- Detailed discrete-event simulation is used to determine exact FMS performance statistics, based on the physical arrangement of machines, tape times, and desired scheduling/dispatching strategies. It is a "fine-tuning" tool, allowing analysis of small changes to the system.
- Production of each parts group was simulated using the optimum FMS design indicated by MVAQ in Step 6. The desired number of fixtures for each part was determined through iterative simulations. The scheduling/dispatching rule used was to maintain a balanced production rate for each part -- the "percentage of production completed" for each part was maintained evenly across all of the parts for the entire parts group production time.
- Simulation results for a one-week period for each parts group are included for review in this section.
- The simulations indicated that production levels could be achieved using the optimum FMS design within the time allowed for 75% utilization of the system.
- The simulations indicated that only one part, 10895603, requires two fixtures of each fixture type for that part. All other parts require only one fixture per fixture type for that part.

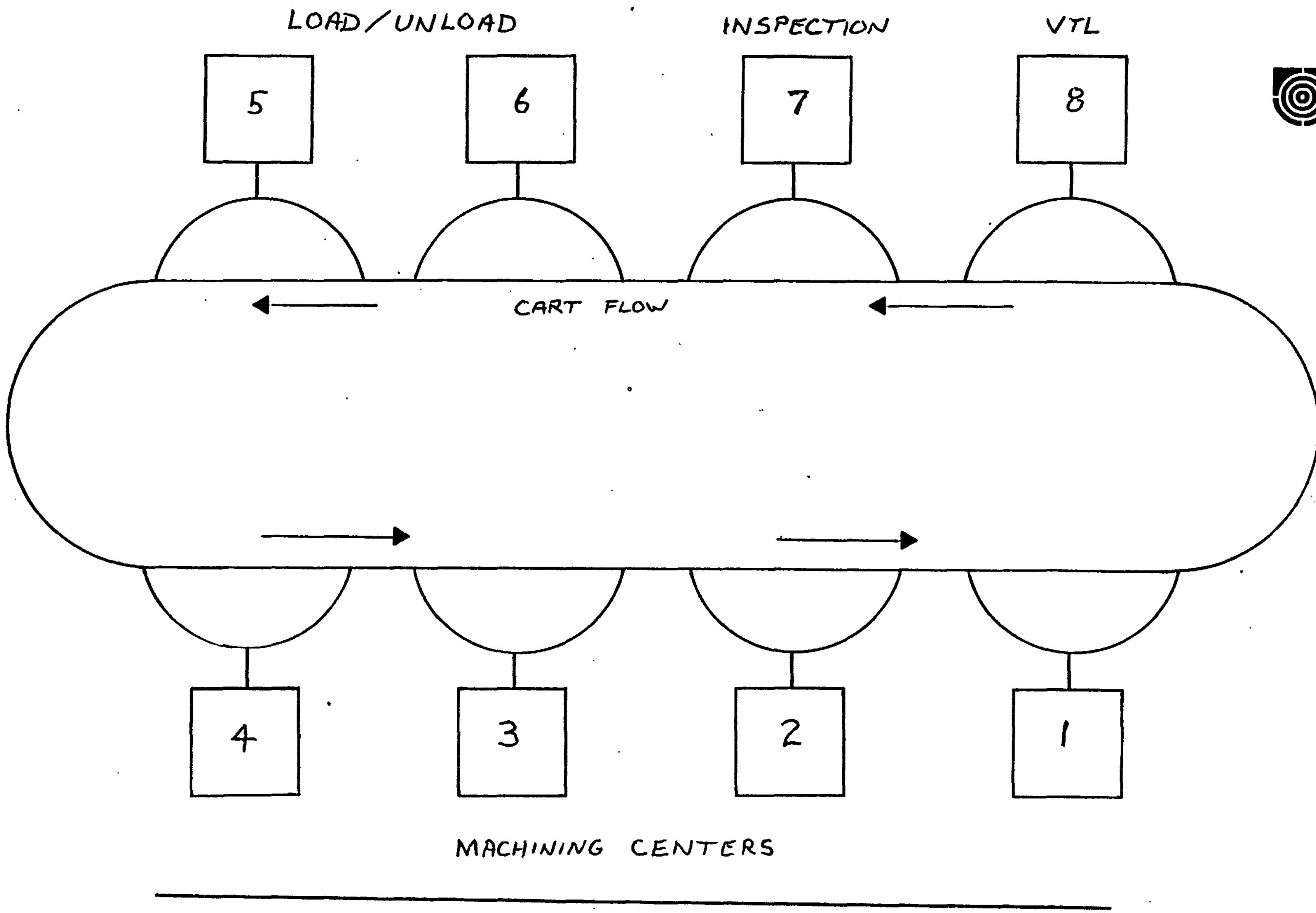

Figure 15. Floor Plan of Simulated FMS

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PRODUCTION SUMMARY FOR COMPLETED PARTS

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PART TYPE	-- PART PRODUCTION -- REQD	SCHED	COMP	PCT	SIDE TYPE	-- SIDE PRODUCTION -- REQD	SCHED	COMP	PCT	SIDE TIME IN SYSTEM AVE	MIN	MAX	AVE. NUM. IN SYSTEM
1	126	4	4	3.2	1	126	4	4	3.2	72.32	38.28	113.26	0.06
2	126	4	4	3.2	2	126	4	4	3.2	112.58	87.96	145.64	0.09
3	252	8	7	2.8	3	252	8	7	2.8	100.06	36.00	166.74	0.14
					4	252	7	7	2.8	178.58	59.28	308.86	0.25
4	378	11	11	2.9	5	378	11	11	2.9	125.07	57.58	248.75	0.28
					6	378	11	11	2.9	239.54	79.60	373.56	0.53
5	378	11	11	2.9	7	378	11	11	2.9	147.44	96.56	309.32	0.32
6	100	3	3	3.0	8	100	3	3	3.0	172.24	101.16	253.33	0.10
7	1134	33	32	2.8	9	1134	33	33	2.9	64.77	19.07	179.50	0.43
					10	1134	33	33	2.9	76.82	18.74	312.05	0.51
					11	1134	33	32	2.8	224.78	26.30	362.46	1.44
8	600	17	17	2.8	12	600	17	17	2.8	180.28	66.33	305.56	0.61
9	600	17	16	2.7	13	600	17	17	2.8	206.00	28.95	413.92	0.70
					14	600	17	16	2.7	115.31	29.58	255.31	0.37
10	567	17	16	2.8	15	567	17	16	2.8	112.70	32.30	285.69	0.36
11	75	3	2	2.7	16	75	3	3	4.0	309.24	140.93	441.36	0.19
					17	75	3	2	2.7	173.90	159.64	188.15	0.07
12	567	16	16	2.8	18	567	16	16	2.8	332.42	127.03	443.26	1.06
					19	567	16	16	2.8	156.99	73.67	434.29	0.50
13	567	26	25	4.4	20	567	26	25	4.4	231.22	48.55	402.51	1.16
					21	567	25	25	4.4	213.02	29.40	446.98	1.07
14	252	12	11	4.4	22	252	12	11	4.4	129.11	55.49	244.54	0.28
					23	252	11	11	4.4	222.35	74.85	376.09	0.49
15	252	12	10	4.0	24	252	12	11	4.4	268.60	212.04	394.01	0.59
					25	252	11	11	4.4	150.63	68.60	213.07	0.33
					26	252	11	10	4.0	379.98	291.09	529.73	0.76
16	252	12	10	4.0	27	252	12	11	4.4	384.29	325.35	446.76	0.85
					28	252	11	10	4.0	275.66	223.78	314.97	0.55
17	254	12	11	4.3	29	254	12	12	4.7	122.36	48.55	277.42	0.29
					30	254	12	11	4.3	127.36	70.55	268.66	0.28
18	254	12	12	4.7	31	254	12	12	4.7	152.87	101.29	239.98	0.37
19	100	5	4	4.0	32	100	5	5	5.0	393.48	341.31	497.58	0.39
					33	100	5	4	4.0	314.94	281.11	345.52	0.25
20	100	5	4	4.0	34	100	5	5	5.0	358.72	193.65	470.26	0.36
					35	100	5	4	4.0	119.23	53.94	277.54	0.10
21	100	5	4	4.0	36	100	5	5	5.0	216.37	126.26	330.50	0.22
					37	100	5	5	5.0	119.41	81.66	161.00	0.12
					38	100	5	5	5.0	86.28	65.60	117.12	0.09
					39	100	5	4	4.0	309.73	248.84	371.77	0.25
22	600	28	26	4.3	40	600	28	27	4.5	79.77	18.20	212.77	0.43
					41	600	27	26	4.3	80.88	27.07	211.18	0.42
23	600	28	26	4.3	42	600	28	27	4.5	82.18	16.20	212.41	0.44
					43	600	27	26	4.3	92.02	24.89	290.79	0.48
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	TOTAL	301	282				581	562					

Figure 16. Simulation Results, Parts Group 1 (Part 1 of 4)

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PALLET INFORMATION
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PALL TYPE	-IN USE- AVE	NOW	NOW AVAIL	MIN USED	MAX USED
1	0.19	0	2	0	2
2	0.14	1	1	0	1
3	0.31	0	2	0	1
4	0.32	0	2	0	1
5	0.57	0	2	0	2
6	0.37	0	2	0	1
7	0.16	0	2	0	1
8	0.43	0	2	0	2
9	0.51	0	2	0	2
10	1.45	1	1	0	2
11	0.65	0	2	0	2
12	0.71	0	2	0	2
13	0.37	1	1	0	2
14	0.36	1	1	0	2
15	0.19	0	2	0	1
16	0.07	1	1	0	1
17	1.10	0	2	0	2

Figure 16. Simulation Results, Parts Group 1 (Part 2 of 4)

18	0.51	0	2	0	2
19	1.16	1	1	0	2
20	1.07	0	2	0	2
21	0.29	1	1	0	1
22	0.50	0	2	0	1
23	0.60	1	1	0	2
24	0.35	0	2	0	1
25	0.80	1	1	0	2
26	0.86	1	1	0	2
27	0.58	1	1	0	1
28	0.30	0	2	0	1
29	0.29	1	1	0	1
30	0.37	0	2	0	1
31	0.77	0	2	0	2
32	0.36	2	0	0	2
33	0.23	0	2	0	1
34	0.12	0	2	0	1
35	0.09	0	2	0	1
36	0.25	1	1	0	1
37	0.88	2	0	0	2
38	0.91	2	0	0	2

Figure 16. Simulation Results, Parts Group 1 (Part 3 of 4)

STATION PERFORMANCE SUMMARY

STATION NUMBER	TIME BUSY	PCT	TIME IDLE	PCT	TIME TRANS OUT	PCT	TIME TRANS IN	PCT	TIME DOWN	PCT	PER CENT OF TIME BUSY DURING TIME AVAILABLE
1	4189.59	83.8	809.45	16.2	0.48	0.0	0.49	0.0	0.00	0.0	83.81
2	4697.87	94.0	299.45	6.0	1.34	0.0	1.35	0.0	0.00	0.0	94.01
3	3837.19	76.7	1161.15	23.2	0.82	0.0	0.83	0.0	0.00	0.0	76.78
4	3330.43	66.6	1667.75	33.4	0.91	0.0	0.91	0.0	0.00	0.0	66.65
5	2289.00	45.8	2685.38	53.7	13.24	0.3	12.38	0.2	0.00	0.0	46.29
6	3177.44	63.5	1792.19	35.8	15.62	0.3	14.74	0.3	0.00	0.0	64.16
7	1479.25	29.6	3515.38	70.3	2.66	0.1	2.72	0.1	0.00	0.0	29.69
8	3036.83	60.7	1958.78	39.2	2.16	0.0	2.22	0.0	0.00	0.0	60.82

Figure 16. Simulation Results, Parts Group 1 (Part 4 of 4)

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PRODUCTION SUMMARY FOR COMPLETED PARTS
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PART	-- PART PRODUCTION --				SIDE	-- SIDE PRODUCTION --				SIDE TIME IN SYSTEM			AVE. NUM.
TYPE	REQD	SCHED	COMP	PCT	TYPE	REQD	SCHED	COMP	PCT	AVE	MIN	MAX	IN SYSTEM
1	201	23	21	10.4	1	201	23	23	11.4	59.41	27.03	102.59	0.27
					2	201	23	22	10.9	60.09	23.81	97.49	0.26
					3	201	22	21	10.4	84.60	38.88	144.31	0.36
2	126	15	14	11.1	4	126	15	14	11.1	71.78	46.60	115.41	0.20
					5	126	14	14	11.1	135.48	111.80	155.20	0.38
					6	126	14	14	11.1	103.25	51.13	139.51	0.29
3	126	15	14	11.1	7	126	15	14	11.1	94.55	62.05	134.99	0.26
					8	126	14	14	11.1	97.93	90.73	120.19	0.27
4	126	14	14	11.1	9	126	14	14	11.1	121.65	79.35	159.17	0.34
					10	126	14	14	11.1	63.74	46.41	89.86	0.18
5	126	14	14	11.1	11	126	14	14	11.1	69.68	42.60	136.05	0.20
6	126	14	14	11.1	12	126	14	14	11.1	52.46	33.96	69.17	0.15
					13	126	14	14	11.1	59.19	33.50	85.66	0.17
7	126	14	14	11.1	14	126	14	14	11.1	71.03	52.80	114.77	0.20
					15	126	14	14	11.1	55.12	29.72	81.30	0.15
8	126	14	14	11.1	16	126	14	14	11.1	54.68	37.60	94.63	0.15
					17	126	14	14	11.1	57.17	41.60	78.03	0.16
9	133	15	15	11.3	18	133	15	15	11.3	64.98	29.60	108.02	0.19
10	133	15	14	10.5	19	133	15	15	11.3	69.19	29.78	136.20	0.21
					20	133	15	14	10.5	75.37	29.40	115.41	0.21
11	250	28	27	10.8	21	250	28	28	11.2	52.09	12.74	97.85	0.29
					22	250	28	27	10.8	53.43	22.77	95.74	0.29
12	50	6	6	12.0	23	50	6	6	12.0	45.03	27.51	67.21	0.05
					24	50	6	6	12.0	80.31	50.61	117.12	0.10
13	106	12	12	11.3	25	106	12	12	11.3	78.68	56.01	122.60	0.19
					26	106	12	12	11.3	51.83	30.61	95.33	0.12
14	600	67	67	11.2	27	600	67	67	11.2	46.50	16.46	105.40	0.62
15	567	63	63	11.1	28	567	63	63	11.1	51.91	19.83	116.52	0.65
16	378	42	40	10.6	29	378	42	41	10.8	112.36	69.07	165.24	0.92
					30	378	41	40	10.6	71.37	27.65	114.12	0.57
17	254	29	27	10.6	31	254	29	28	11.0	102.27	48.90	159.97	0.57
					32	254	28	27	10.6	70.68	27.65	139.01	0.38
18	252	28	28	11.1	33	252	28	28	11.1	93.82	44.70	171.40	0.53
19	252	33	32	12.7	34	252	33	32	12.7	56.83	24.95	135.76	0.36
20	252	33	31	12.3	35	252	33	32	12.7	54.25	24.37	109.01	0.35
					36	252	32	32	12.7	59.44	15.98	114.40	0.38
					37	252	32	31	12.3	66.66	36.25	115.41	0.41
21	76	10	10	13.2	38	76	10	10	13.2	63.19	48.77	94.67	0.13
22	567	72	70	12.3	39	567	72	71	12.5	59.64	21.33	112.17	0.85
					40	567	71	70	12.3	52.38	20.02	101.30	0.73
23	51	7	7	13.7	41	51	7	7	13.7	57.32	39.73	75.98	0.08
					42	51	7	7	13.7	59.85	38.47	94.05	0.08
24	268	35	34	12.7	43	268	35	34	12.7	85.75	24.50	161.86	0.58

Figure 17. Simulation Results, Parts Group 2 (Part 1 of 6)

					44	268	34	34	12.7	66.11	32.40	100.50	0.45
25	201	26	25	12.4	45	201	26	26	12.9	55.02	24.97	88.34	0.29
					46	201	26	25	12.4	76.62	55.94	109.85	0.38
26	106	14	14	13.2	47	106	14	14	13.2	70.27	48.97	88.90	0.20
					48	106	14	14	13.2	53.03	34.97	73.13	0.15
					49	106	14	14	13.2	115.66	75.76	143.12	0.32
27	106	14	14	13.2	50	106	14	14	13.2	82.02	54.70	115.30	0.23
					51	106	14	14	13.2	94.00	47.89	132.80	0.26
					52	106	14	14	13.2	70.24	50.41	97.29	0.20
28	201	26	25	12.4	53	201	26	26	12.9	56.18	18.98	116.69	0.29
					54	201	26	25	12.4	57.52	33.61	105.11	0.29
29	212	27	27	12.7	55	212	27	27	12.7	156.44	66.09	245.99	0.84
					56	212	27	27	12.7	53.24	29.43	99.67	0.29
30	100	13	12	12.0	57	100	13	13	13.0	133.36	102.04	158.91	0.35
					58	100	13	13	13.0	78.76	48.95	112.59	0.20
					59	100	13	12	12.0	90.45	58.46	135.77	0.22
		-----	-----				-----	-----					
	TOTAL	738	719				1348	1329					

Figure 17. Simulation Results, Parts Group 2 (Part 2 of 6)

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PALLET INFORMATION
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PALL TYPE	-IN AVE	USE- NOW	NOW AVAIL	MIN USED	MAX USED
1	0.27	0	2	0	1
2	0.26	1	1	0	1
3	0.36	1	1	0	2
4	1.19	2	0	0	2
5	0.75	0	2	0	2
6	0.22	1	1	0	1
7	0.21	0	2	0	1
8	0.36	0	2	0	2
9	0.33	0	2	0	2
10	0.16	0	2	0	1
11	0.17	0	2	0	1
12	0.20	0	2	0	1
13	0.21	0	2	0	1
14	0.21	1	1	0	1
15	0.29	0	2	0	1
16	0.29	1	1	0	1

Figure 17. Simulation Results, Parts Group 2 (Part 3 of 6)

17	0.06	0	2	0	1
18	0.10	0	2	0	1
19	0.19	0	2	0	1
20	0.13	0	2	0	1
21	0.62	0	2	0	2
22	0.66	0	2	0	2
23	0.93	1	1	0	2
24	0.58	1	1	0	2
25	0.58	1	1	0	2
26	0.38	1	1	0	2
27	0.53	0	2	0	2
28	0.36	1	1	0	1
29	0.35	1	1	0	1
30	0.38	0	2	0	1
31	0.42	1	1	0	2
32	0.13	0	2	0	1
33	0.85	1	1	0	2
34	0.74	1	1	0	2
35	0.09	0	2	0	1
36	0.09	0	2	0	1

Figure 17. Simulation Results, Parts Group 2 (Part 4 of 6)

37	0.59	1	1	0	2
38	0.45	0	2	0	2
39	0.29	0	2	0	1
40	0.39	1	1	0	1
41	0.44	0	2	0	2
42	0.42	0	2	0	2
43	0.52	0	2	0	2
44	0.29	0	2	0	1
45	0.29	1	1	0	1
46	0.85	0	2	0	2
47	0.29	0	2	0	1
48	0.36	0	2	0	1
49	0.21	0	2	0	1

Figure 17. Simulation Results, Parts Group 2 (Part 5 of 6)

STATION PERFORMANCE SUMMARY

STATION NUMBER	TIME BUSY	PCT	TIME IDLE	PCT	TIME TRANS OUT	PCT	TIME TRANS IN	PCT	TIME DOWN	PCT	PER CENT OF TIME BUSY DURING TIME AVAILABLE
1	4905.80	98.1	89.53	1.8	2.33	0.0	2.34	0.0	0.00	0.0	98.21
2	3828.38	76.6	1166.70	23.3	2.46	0.0	2.46	0.0	0.00	0.0	76.67
3	4619.59	92.4	374.51	7.5	2.95	0.1	2.96	0.1	0.00	0.0	92.51
4	4707.82	94.2	285.98	5.7	3.09	0.1	3.10	0.1	0.00	0.0	94.28
5	4147.44	82.9	782.75	15.7	35.74	0.7	34.06	0.7	0.00	0.0	84.34
6	4183.57	83.7	753.27	15.1	31.72	0.6	31.43	0.6	0.00	0.0	84.93
7	2946.01	58.9	2040.44	40.8	6.77	0.1	6.77	0.1	0.00	0.0	59.19
8	4419.57	88.4	575.69	11.5	2.36	0.0	2.37	0.0	0.00	0.0	88.49

Figure 17. Simulation Results, Parts Group 2 (Part 6 of 6)

Table 11. Production Rates Obtainable

No.	Part Number	Name	End Item	Required Annual Quantity	MVAQ Projected Quantity	Simulation Projected Quantity
1	10884271	BRACKET	M140	399	432	528
2	10891945	GEAR, GUN ELEVATING (MACH)	M174	106	126	132
3	10892028	HOUSING (MACH-CAST)	M174	100	110	108
4	10895603	FOLLOWER FRONT	M178	1134	1325	1188
5	10895627	HOUSING (MACH)	M178	599	718	612
6	10895673	HOUSING (MACH)	M178	599	718	612
7	10895694	COVER (MACHINING)	M178	567	663	576
8	10895695	BEARING SLEEVE (MACHINING)	M178	599	718	936
9	10895696	BEARING SLEEVE (MACHINING)	M178	599	718	936
10	10909285	KEY, TORQUE (MACHINING)	M178	567	664	624
11	10922978	BRACKET CAM MOUNTING (MACH)	M178	599	680	864
12	10923025	LEVER CAM (MACH)	M178	567	647	576
13	10930330	CAM BREECH OPERATING	M178	567	663	624
14	10933932	BRACKET	M140	378	431	440
15	11590764		M1	254	291	297
16	11636292	MANIFOLD.REPL.SYS	M178	567	663	900
17	12007690	ADAPTOR (MACH)	M45	252	291	308
18	12007719	YOKE MIDDLE ASSEMBLY	M45	252	303	396
19	12007721	BODY	M45	252	303	360
20	12007723	YOKE REAR (MACH)	M45	252	303	360
21	12007725	BRACKET (MACH)	M45	252	291	352
22	12007765	END	M45	252	291	341
23	12007772	CLAMP (MACH)	M45	756	860	1100
24	12012132	COVER TUBING	M178	567	636	770
25	12274291		M1	254	303	396
26	12274293		M1	254	303	396
27	12274327		M1	504	540	770
28	12274331		M1	268	313	374
29	5507255	GUIDE (MACH)	M174	201	216	286
30	5509262	TRUNNION LEFT HAND	M174	106	129	154
31	5509263	TRUNNION RIGHT HAND	M174	106	129	154
32	5568984	HEAD	M174	201	216	275
33	6105074	BRACKET	M174	212	237	297
34	6505782	CAP TRUNNION LEFT (MACH)	M174	100	110	144
35	6505788	CAP TRUNNION RIGHT (MACH)	M174	100	110	144
36	6507039	YOKE	M174	100	110	144
37	6536154	BOCY REGULATOR	M174	100	118	132
38	8430397	HEAD	M174	201	216	231
39	8432870	YOKE ASSY FRONT (MACHINING)	M102	126	151	154
40	8432887	YOKE REAR	M102	126	151	154
41	8432888	YOKE CENTER (MACHINING)	M102	126	151	154
42	8432977	BRACKET ASSEMBLY	M102	126	151	154
43	8433535	BRACKET	M102	126	138	144
44	8433536	BRACKET RIGHT	M102	126	138	144
45	8433634	SUPPORT ASSEMBLY R.H.(MACH)	M102	126	151	154
46	8433635	SUPPORT ASSEMBLY L.H.(MACH)	M102	126	151	154
47	8433716	YOKE (MACHINING)	M102	126	151	154
48	8433724	HOUSING (MACH)	M102	133	151	165
49	8433797	HOUSING.GEAR	M102	252	303	252
50	8447496	HOUSING	M102	133	151	165
51	8449308	BRACKET SUPPORT (MACHINING)	M140	378	442	396
52	8449309	BRACKET TORQUE (MACHINING)	M140	378	442	396
53	8432951	HOUSING UPPER		250	291	297

Note: No part failed to meet production targets in either MVAQ or SIM scenarios.

2.8 STEP 8: PERFORM ECONOMIC ANALYSIS

- The FMS was examined in two categories of economic analysis -- capacity expansion and machine replacement.

- Capacity expansion analysis assumes that some equipment must be purchased to expand capacity, and compares various investment strategies to find the solution with the smallest investment or best incremental return on investment.

- Machine replacement analysis assumes that equipment currently in use may be less efficient than some new equipment, and compares various investment strategies to the current method to find a better approach (if any) with the best incremental return on investment.

- Client is currently in a capacity expansion mode, which will be the primary FMS analysis category. However, the question was raised as to what the difference would be if client had already purchased stand-alone machines instead of an FMS. As a second economic analysis exercise, it will be assumed that client has the same type of stand-alone CNC machines as those that will be in the FMS, and wants to replace them with an FMS, to determine what range of return on investment might be expected from an FMS (if any).

- Both evaluations are conservative, biased against the FMS.

- For both investment categories, the FMS is the most appropriate investment strategy.

2.8.1 Economic Evaluation Parameters

- Before tax analysis only.
- No work-in-process inventory reduction.
- No estimate of material handling cost reduction.
- Installation cost - $25,000 per machine.
- Direct labor cost, machine operator - $15.59/hour, $42.08/hour overhead. ($10.94 variable overhead, $31.14 fixed overhead).
- Direct labor cost, inspector - $16.56/hour, $14.41 overhead.
- Floor space cost - $2/sq. ft. annually in the NC machine shop.
- Floor space cost - $1.75/sq. ft. annually for storage.
- Supervisor/operator ratio - 1:14.
- Current rework cost - 4% of direct labor hours.
- Tape proveout costs - considered equal for both methods.
- Client would buy dedicated fixtures in the stand-alone CNC cases, but would not purchase an AS/RS to store them.

Available Production Hours Annually

240 Days x 8 Hours/Shift x 2 Shifts	=	3,840 Hours
At 75% Efficiency	=	2,880 Hours

2.8.2 Client Economic Analysis, Capacity Expansion

2.8.2.1 Stand-Alone NC Machine Tool Utilization

Presented below are current machine tool utilization figures (per Client Sampling Study, assuming pallet changing NC machines.)

Uptime	
Set-up	11.0%
Machining Cycle	23.2%
	34.2%
Downtime	
No Job	1.2%
No Operator	8.2%
Breakdown	17.1%
Overhead	2.9%
Warm-up	0.5%
Prove-out	6.2%
Personal	6.6%
Miscellaneous	6.8%
Rework	4.7%
Operator Manipulation	11.6%
	65.8%

2.8.2.2 Average FMS Machine Tool Utilization

Uptime	
Machining Cycle	75.0%
Downtime	
Breakdown	8.0%
Preventive Maintenance	4.0%
Prove-Out	6.2%
Rework	2.4%
Miscellaneous	4.4%
	25.0%

Prove-out and rework, usually done off-line, are included to equalize the comparison. Average rework time for FMS production is usually less than half of the current percentage on a factory-by-factory basis. So half of the current client figure was used for rework.

2.8.2.3 FMS Requirements

- Assumed FMS machine utilization: 75%
- Available time, annually = 240 x 2 x 8 = 3,840 hours
- Actual FMS production time available annually:

  3,840 x 0.75 = 2,880 hours
- Total Horizontal Machining Center Hours required: 9,678.60 hours
- Number of horizontal machining centers needed:

  9,678.60/2,880 = 3.36 = 4 machines
- Total vertical turret lathe hours required: 1,817.7 hours
- Number of VTL's needed:

  1,817.7/2,880 = 0.63 = 1 machine
- Total load/unload hours required: 4,164.8 hours
- Number of load/unload stations needed:

  4,164.8/2,880 = 1.45 = 2
- Total inspection hours required: 1,299.8 hours
- Number of inspection stations needed:

  1,299.8/2,880 = 0.45 = 1 machine

2.8.2.4 FMS Investment (See Step 4 for Capacity Requirements)

4	4-Axis Machining Centers, 90-tool storage $580,000 each (20 HP) (includes 8 pallets, chip conveyor, flood coolant)	$2,320,000	
1	Bullard or Gray VTL, 12-tool changer $900,000 each	900,000	
1	Material Handling System, wire-guided vehicles (2)	680,000	
1	Automatic Storage/Retrieval System store up to 150 pallets	450,000	Installed
1	DEA Bravo Inspection Robot	150,000	Installed
1	Computer Control	650,000	
1	Master Alignment Pallet	9,000	
90	Pallets, $8,000 each	720,000	
101	Fixtures, $20,000 each	2,020,000	
1080	Tool Holders, $150 each (3 sets)	162,000	
1	Computer Room	30,000	
	Installation, $25,000/machine	125,000	
	Total	$8,216,000	

2.8.2.5 Client Stand-Alone Machine Tool Requirements

- Assumed client stand-alone machine utlization: 34.2%
- Actual production time available annually

  3840 hours x 0.342 = 1313.26

- Total horizontal machining center hours required: 9,678.6 hours.

  Number of machining centers needed for 34.2 utilization:

  9678.6/1313.28 = 7.37 = 8 machines

- Total vertical turret lathes hours required: 1,817.7 hours

  Number of VTL's needed for 34.2% utilization

  1,817.7/1,313.28 = 1.38 = 2 machines

- Total inspection hours required: 1,299.8 hours

  Number of inspection stations needed at 34.2% utilization

  1,299.8/1,313.28 = 0.99 = 1 machine

2.8.2.6 Client Stand-Alone Machine Tool Investment

8	NC Machining Centers, same as those in FMS $580,000 each, with pallets, changer	$4,640,000
2	VTL's, $900,000 each	1,800,000
1	Inspection Robot	150,000
79	Pallets, $8,000 each	632,000
101	Fixtures, $20,000 each	2,020,000
2160	Tool Holders, $150 each (3 sets)	324,000
	Installation, $25,000 per machine	250,000
	Total	$9,816,000

2.8.2.7 Manpower, Per Shift

FMS	Stand-Alone
Direct Labor, Inspector for Process Verification Only	
System Manager	0.79 Foreman
2 Load/Unload Personnel	10 Operators
1 Rover	1 Inspector
1 Inspector	-
5	11.79

Total Manpower, 2 Shifts:
FMS - 10
CLIENT - 23.58

2.8.2.8 Manufacturing Costs - Stand-Alone

Direct Labor Cost

Client = 240 x 2 x 8 x 10.79 x 15.59 = $645,949.82 Operators
Client = 240 x 2 x 8 x 1 x 16.56 = 63,500.40 Inspectors

$709,450.22 Direct Labor Annually

Variable Overhead Cost

Client = 240 x 2 x 8 x 11.79 x 10.94 = $495,293.18 Overhead Annually

Fixed Overhead Allocation Basis - Floor Space

Per Machine - 1,500 sq. ft. (600 sq. ft. for the inspection robot)
Includes Local Storage Space for Work-in-Process Inventory

Total for Machines = 10 x 1,500 = 15,000 + 600 =	15,600 sq. ft.
Supervisor's Office	375 sq. ft.
Material Handling Aisle	4,800 sq. ft.
Allocation basis for fixed overhead	20,775 sq. ft.

Client 240 x 2 x 8 x 11.79 x 31.14 = $1,409,819.90 Annually

Total Annual Manufacturing Costs for Client:

Direct Labor	=	$ 709,450.22
Variable Overhead	=	495,293.18
Fixed Overhead	=	1,409,819.90
		$2,614,563.30

2.8.2.9 Manufacturing Costs (Direct Labor and Overhead) - FMS

Direct Labor Cost

FMS = 240 days x 2 shifts x 8 hours x 4 x $15.59 =	$239,462.40	Operators
240 days x 2 shifts x 8 hours x 1 x $16.56 =	63,590.40	Inspector
	$303,052.80	Direct Labor Annually

Variable Overhead Cost

Assume variable overhead per machine is the same as for client, $10.94/hour. The material handling portion of current overhead will be assumed to cover the material handling system. This is conservative.

FMS = 240 x 2 x 8 x 5 x $10.94 = $210,048.00 Variable Overhead Annually

It is assumed that fixed overhead is allocated on some constant basis by department; the most common basis is floor space. To estimate the share of fixed overhead to be allocated to the FMS, the floor space requirements for each alternative (stand-alone an FMS) were calculated. The overhead cost was assumed to be that calculated for the stand-alone case. It is assumed that other manufacturing equipment would occupy the floor space freed by choosing an FMS over the stand-alone alternative. Therefore, the FMS is allocated only a portion of the fixed overhead. The fraction of the overhead pool allocated to the FMS is the ratio of the floor space for the FMS to the floor space for the stand-alone alternative.

Fixed Overhead Allocation Basis - Floor Space

Per Machine - 900 sq. ft. (400 sq. ft. for the inspection robot)

Total for Machines - 5 x 900 = 4,500 + 400 =	4,900 sq. ft.
Load/Unload Station - 400 sq. ft. - Total =	800 sq. ft.
Computer Room - 375 sq. ft.	375 sq. ft.
Material Handling System	2,000 sq. ft.
AS/RS	1,200 sq. ft.
	9,275 sq. ft.

Fixed Overhead Cost

FMS = 9,275/20,775 x 1,409,819.90 = $629.413.73 annually

FMS - Total Annual Manufacturing Costs:

Direct Labor	=	$ 303,052.80
Variable Overhead	=	210,048.00
Fixed Overhead	=	629,413.73
		$1,142,514.53

2.8.2.10 Capacity Expansion Study Summary

	FMS	Stand-Alone
Total Investment	$8,216,000.00	$9,816,000.00
Total Annual Manufacturing Cost	$1,142,514.53	$2,614,563.30

- Material costs are assumed to be equal, although an FMS usually has a lower scrap rate than similar stand-alone machines.
- Rework costs are assumed to be buried in overhead for both alternatives, although an FMS usually has a rework rate of 50% of the stand-alone machines.
- Since the FMS is both the smaller investment and less costly manufacturing method, it should be installed instead of the equivalent number of stand-alone CNC machine tools required for equal production.

2.8.3 Client Economic Analysis, Machine Replacement

- Assume client has a sufficient stand-alone quantity of the same type of CNC machines that would be in the FMS. These machines have pallet changers, but no dedicated fixtures or tools have been purchased for the parts. Fixtures are stored in rack areas; no AS/RS will be purchased for the stand-alone alternative.
- Work-in-process inventory reduction is not to be considered.
- Before-tax analysis.

2.8.3.1 FMS Investment

Same as before, less fixtures, pallets, and tool holders, which would have to be purchased for both the FMS and stand-alone alternatives.

FMS Investment = $5,314,000.00

2.8.3.2 Cost Savings Due to FMS Implementation

- In year 1

Stand-Alone Manufacturing Cost (from before)	=	2,614,563.30
FMS Manufacturing Cost (from before)	=	$1,142,514.53
Net Savings Due to FMS Implementation	=	$1,472,048.77

- Assume the annual manufacturing costs for both alternatives will increase at the rate of inflation, 7%.
- Assume these manufacturing costs are representative of the costs for both alternatives for the first five years.
- Assume that the stand-alone CNC machines will not be sold to offset the cost of the FMS.
- Annual cash flow from FMS:

Year	Cash Flow
0	-$5,314,000.00
1	1,472,048.77
2	1,575,092.18
3	1,685,348.63
4	1,803,323.65
5	1,929,555.65

ROI = 17%

2.8.3.2 Continued

- If these manufacturing costs are representative of the cost for both alternatives for the first seven years:

  - Annual cash flow from FMS:

Year	Cash Flow
0	-$5,314,000.00
1	1,472,048.77
2	1,575,092.18
3	1,685,348.63
4	1,803,323.04
5	1,929,555.65
6	2,064,624.50
7	2,209,148.26

ROI = 24%

- If these costs are representative for the first ten years:

  - Annual cash flow from FMS:

Year	Cash Flow
0	-$5,314,000.00
1	1,472,048.77
2	1,575,092.18
3	1,685,348.63
4	1,803,323.04
5	1,929,555.65
6	2,064,624.50
7	2,209,148.26
8	2,363,788.64
9	2,529,253.84
10	2,706,301.62

ROI = 30%

- If all of the stand-alone CNC machines could be sold for one quarter of their original price to offset the price of the FMS:

Machine tool sales, year 0 = 0.25 x 6,440,000 = $1,610,000.

2.8.3.2 Continued

- Annual cash flow from FMS (five-year period):

Year	Cash Flow
0	-$5,314,000.00 + 1,610,000 = -$3,704,000
1	1,472,048.77
2	1,575,092.18
3	1,685,348.63
4	1,803,323.04
5	1,929.555.64

ROI = 36%

- Since the FMS has a return on investment better than inflation in all cases, it should be installed to replace the current CNC machine tools.

2.8.4 Worst Case Analysis, Capacity Expansion

2.8.4.1 FMS Requirements

- Assumed FMS machine utilization: 50%
- Available time, annually = 240 x 2 x 8 = 3,840 hours
- Actual FMS production time available annually:

  3,840 x 0.50 = 1,920 hours
- Total Horizontal Machining Center Hours required: 9,678.60 hours
- Number of horizontal machining centers needed:

  9,678.60/1,920 = 5.04 = 6 machines
- Total vertical turret lathe hours required: 1,817.7 hours
- Number of VTL's needed:

  1,817.7/1,920 = 0.95 = 1 machine
- Total load/unload hours required: 4,164.8 hours
- Number of load/unload stations needed:

  4,164.8/1,920 = 2.17 = 3
- Total inspection hours required: 1,299.8 hours
- Number of inspection stations needed:

  1,299.8/1,920 = 0.68 = 1 machine

2.8.4.2 FMS Investment

6	Machining Centers	$580,000/each	= $3,480,000
1	VTL		= $ 900,000
1	MHS, 2 Vehicles		= $ 680,000
1	AS/RS		= $ 450,000
1	Inspection Robot		= $ 150,000
1	Computer Control		= $ 650,000
1	Master Alignment Pallet		= $ 9,000
90	Pallets	$ 8,000/each	= $ 720,000
101	Fixtures	$ 20,000/each	= $2,020,000
1,620	Tool Holders	$ 150/each	= $ 243,000
1	Installation, $25,00 per machine		= $ 175,000
	Computer Room		$ 30,000
			$9,507,000

2.8.4.3 Client Stand-Alone Machine Tool Requirements

- Assumed client stand-alone machine utilization: 28.5%
- Actual production time available annually:

  3,840 x 0.285 = 1,094.4 hours
- Total horizontal machining center hours required: 9,678.60 hours
- Number of horizontal machining centers needed:

  9,678.60/1,094.4 = 8.84 = 9 machines
- Total vertical turret lathe hours required: 1,817.7 hours
- Number of VTL's needed:

  1,817.7/1,094.4 = 1.67 = 2 machines
- Total inspection hours required: 1,299.8 hours
- Number of inspection stations needed:

  1,299.8/1,094.4 = 1.19 = 2 machines

2.8.4.4 Client Stand-Alone Machine Tool Investment

9	Machining Centers	$580,000/each =	$ 5,220,000
2	VTL	$900,000/each =	$ 1,800,000
2	Inspection Robots	$150,000/each =	$ 300,000
77	Pallets	$ 8,000/each =	$ 616,000
101	Fixtures	$ 20,000/each =	$ 2,020,000
2,430	Tool Holders	$ 150/each =	$ 364,500
1	Installation, $25,000 per machine	=	$ 275,000
			$10,595,500

2.8.4.5 Manpower, Per Shift

FMS	Stand-Alone
Direct Labor, Inspector for Process	Verification Only
System Manager	Foreman
3 Load/Unload Personnel	11 Operators
1 Rover	2 Inspector
1 Inspector	
6	14

Total Manpower, 2 Shifts:
FMS - 12
CLIENT - 28

2.8.4.6 Manufacturing Costs - Stand-Alone

<u>Direct Labor Cost</u>

Client = 240 x 2 x 8 x 12 x 15.59 = $718,387.20 Operators
Client = 240 x 2 x 8 x 1 x 16.56 = 127,180.80 Inspectors

$845,568.00 Direct Labor Annually

<u>Variable Overhead Cost</u>

Client = 240 x 2 x 8 x 14 x 10.94 = $588,134.40 Overhead Annually

Fixed Overhead Allocation Basis - Floor Space

Per Machine - 1,500 sq. ft. (600 sq. ft. for the inspection robot)	
Total for Machines = 11 x 1,500 = 16,500 + 1,200 =	17,700 sq. ft.
Supervisor's Office	375 sq. ft.
Material Handling Aisle	5,460 sq. ft.
Allocation basis for fixed overhead	23,535 sq. ft.

Fixed Overhead Cost

Client = 240 x 2 x 8 x 14 x 31.14 = $1,674,086.40 Annually

2.8.4.7 Stand-Alone Total Annual Manufacturing Costs

Direct Labor	=	$ 845,568.00
Variable Overhead	=	588,134.40
Fixed Overhead	=	1,674,086.40
		$3,107,788.80

2.8.4.8 Manufacturing Costs - FMS

Direct Labor Cost

FMS = 240 days x 2 shifts x 8 hours x 5 x $15.59 =	$299,328.00	Operators
240 days x 2 shifts x 8 hours x 1 x $16.56 =	63,590.40	Inspector
	$362,918.40	Direct Labor Annually

Variable Overhead Cost

FMS = 240 x 2 x 8 x 6 x $10.94 = $252,057.60 Annually

Fixed Overhead Allocation Basis - Floor Space

Per Machine - 900 sq. ft. (400 sq. ft. for the inspection robot)	
Total for Machines - 7 x 900 = 6,300 + 400 =	6,700 sq. ft.
Load/Unload Station - 400 sq. ft. - Total =	1,200 sq. ft.
Computer Room - 375 sq. ft.	375 sq. ft.
Material Handling System	2,200 sq. ft.
AS/RS	1,200 sq. ft.
Allocation Basis for Fixed Overhead	11,675 sq. ft.

Fixed Overhead Cost

FMS = 11,675/23,535 x 1,674,086.40 = $830.463.51 annually

2.8.4.9 FMS Total Annual Manufacturing Costs for the FMS

Direct Labor	=	$ 362,918.40
Variable Overhead	=	252,057.60
Fixed Overhead	=	830,463.51
		$1,445,439.51

2.8.4.10 Capacity Expansion Study Summary

	FMS	Stand-Alone
Total Investment	$9,507,000.00	$10,595,500.00
Total Annual Manufacturing Cost	$1,445,439.51	$ 3,107,788.80

- Since the FMS is both the smaller investment and less costly manufacturing method, even in the worst case it should be installed instead of an equivalent number of stand-alone CNC machine tools.

2.8.5 Worst Case Analysis, Machine Replacement

2.8.5.1 FMS Investment

Same as before, less fixtures, pallets and tool holders, which would have to be purchased for both the FMS and stand-alone case.

FMS Investment = $6,524,000.00

2.8.5.2 Cost Savings Due to FMS Implementation

In Year 1

Stand-alone Manufacturing Cost	- $3,107,788.80
FMS Manufacturing Cost	$1,455,439.51
Net Savings due to FMS Implementation	$1,662,349.29

- Assume the annual manufacturing costs for both alternatives will increase at the rate of inflation, 7%.
- Assume these manufacturing costs are representative of the costs for both alternatives for the first five years.
- Assume that the stand-alone <u>CNC machines will not be sold</u> to offset the cost of the FMS.
- Annual cash flow from FMS:

Year	Cash Flow
0	-$6,524,000.00
1	1,662,349.29
2	1,778,713.74
3	1,903,223.71
4	2,036,449.37
5	2,179,000.82

ROI = 13%

2.8.5.2 Continued

- If these manufacturing costs are representative of the cost for both alternatives for the first seven years:

  - Annual cash flow from FMS:

Year	Cash Flow
0	-$6,524,000.00
1	1,662,349.29
2	1,778,713.74
3	1,903,223.71
4	2,036,449.37
5	2,179,000.82
6	2,331,530.87
7	2,494,738.04

ROI = 22%

- If these costs are representative for the first ten years:

  - Annual cash flow from FMS:

Year	Cash Flow
0	-$6,524,000.00
1	1,662,349.29
2	1,778,713.74
3	1,903,223.71
4	2,036,449.37
5	2,179,000.82
6	2,331,530.87
7	2,494,736.04
8	2,669,369.70
9	2,856,225.58
10	3,056,161.37

ROI = 29%

- If all of the stand-alone CNC machines could be sold for one quarter of their original price to offset the price of the FMS:

Machine tool sales, year 0 = 0.25 x 7,020,000 = $1,755,000.

2.8.5.2 Continued

- Annual cash flow from FMS (five-year period):

Year	Cash Flow
0	-$6,524,000.00 + 1,755,000 = -$4,769,000
1	1,662,349.29
2	1,788,713.74
3	1,903,223.71
4	2,036,449.37
5	2,179.000.82

ROI = 30%

- Since the FMS has a return on investment better than inflation in all cases, it should be installed to replace the hypothetical current CNC machine tools.

2.9 STEP 9: EVALUATE FMS INTANGIBLES

- Client presonnel must decide as a group what the intangible features of an FMS are and how important each is to client. The weighing of these features will aid in the vendor proposal evaluation phase.

- A list of typical FMS intangibles might include:

  Flexibility.

  Ease of parts group change-over.

  System accuracy.

  Response to rush orders.

  Redundancy.

  Surge capacity.

  Future availability of skilled machine tool operators and set-up personnel.

2.10 STEP 10: IF FMS IS APPROPRIATE, ISSUE AN FMS REQUEST FOR PROPOSAL

- It appears that an FMS is the prime production alternative at client.

- The FMS should include:

  4 Four-axis horizontal CNC machining centers with at least 90 tool storage positions in the tool chain of each machine. We recommend setting the machines off the main transporter loop on separate queue loops, so carts cannot block the main track.

  1 CNC VTL with tool block changer. We would recommend the purchase of two VTL's, for redundancy, if more turning work content can be added to the FMS part set to load the machine.

  1 Inspection robot.

  2 Load/unload stations with empty pallet queues for on-line storage of pallets/fixtures.

  1 AS/RS for long-term part/fixture/pallet storage.

  1 Automated wire-guided vehicle material handling system with three carts -- two active and one for backup.

- Although the FMS was designed using Kearney & Trecker and DEA machine characteristics, we would recommend issuing a Request For Proposal (RFP) to at least three to five FMS vendors, to provide an opportunity for creative solutions to client's production problem.

SECTION B

SYSTEM PERFORMANCE ANALYSIS STUDY

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1.0 SUMMARY

In the period from September 1983 through June 1984, a series of "tool allocation, workload balancing and simulation" studies was made to help plan the operation of the client's new Flexible Manufacturing System (FMS). First, the Draper decision support software tools were calibrated against functionally equivalent vendor software. Then, a series of tool allocation and workload balancing scenarios were created and simulated, with SLAM II-based discrete-event simulation.

The results indicate that the current FMS has the capacity to produce the target 19 part types at the desired 55/month rate. (However, due to tool storage constraints on the machines in the system, only four of the five "critical" parts can be duplicately tooled and still maintain full concurrent production.) If in the future the production rate is to be increased to 75/month, the studies indicate that a fifth machining center should be added to the system.

Also studied were scenarios for: (i) minimizing tool handling at multi-parts groups operations transitions (using software module "TOOL CHANGE" -- see Section 3.4) and (ii) providing a preplan of reaction to out-of-service equipment. Simulation studies also underlined the importance of providing control and scheduling software in the actual system to permit simultaneous use of a common fixture (F0001) by three distinct part types -- hinges, part numbers 12308936, 12295270, and 12308498. This was especially apparent in scenarios studied in which full concurrent production of all parts was not possible ("Configuration 7").

2.0 CALIBRATION OF SOFTWARE TOOLS

2.1 TOOLBAL AND THE TOOL ALLOCATOR

The first task was to calibrate Draper's decision support software tools against the vendor's proprietary equivalent software tools. Draper's TOOLBAL program performs a function similar to the vendor's Tool Allocator program. They both try simultaneously to:

1. assign tools to the system's machines,

2. balance the workloads on the machines,

3. meet casting availability and due dates, and

4. put all of the part types into as few parts groups as possible.

Because optimal solutions are typically not feasible, both programs find suboptimal solutions. However, using identical input data, TOOLBAL and the vendor's Tool Allocator produced very similar results.

2.2 SIMULATORS

The "baseline" comparison of the vendor and Draper simulators was not as straightforward. Either simulator could use as input data the results of either a TOOLBAL run or a Tool Allocator run. However, the vendor typically processes the output of its Tool Allocator with a "Parts Group Scheduler" before sending it to the vendor simulator. The Parts Group Scheduler, in addition to scheduling the transitions between parts groups, will schedule the introduction of part types within a single parts group. That is, if the Parts Group Scheduler feels that the system may become congested during a parts group run, it will phase or delay the introduction of some of the part types in the parts group.

The two simulators produced very similar results when driven by the same delayed introduction schedule derived by the Parts Group Scheduler. However, when all part types were made available at the beginning of a simulation run, the Draper simulator indicated that a week's production could be completed appreciably sooner than the time predicted by the vendor simulator. The difference appeared to be the way in which the system's Automatic Work Changers (AWC's) were modeled. In the machine tool/vendor system the AWC's were modeled as a single 20-position, FIFO-serviced pallet storage device; thus pallets in the queue may experience considerable delay if the destination of the first pallet is blocked for any length of time. The AWC model in the Draper simulator was much closer to the random-access operation of the actual AWC's.

It was concluded that the reason the results of the two simulators compared well when utilizing a "delayed introduction" schedule was that the AWC was relatively unused and, therefore, the difference in the AWC models was unimportant. Further, it was concluded that deferred scheduling was not needed at present, given that there are currently only 21 pallets and there are twice that number of available pallet positions in the system. (See Figure 1 on page 7 for system layout.) Finally, it was concluded that the Draper simulator provided good results and could be relied upon for further studies.

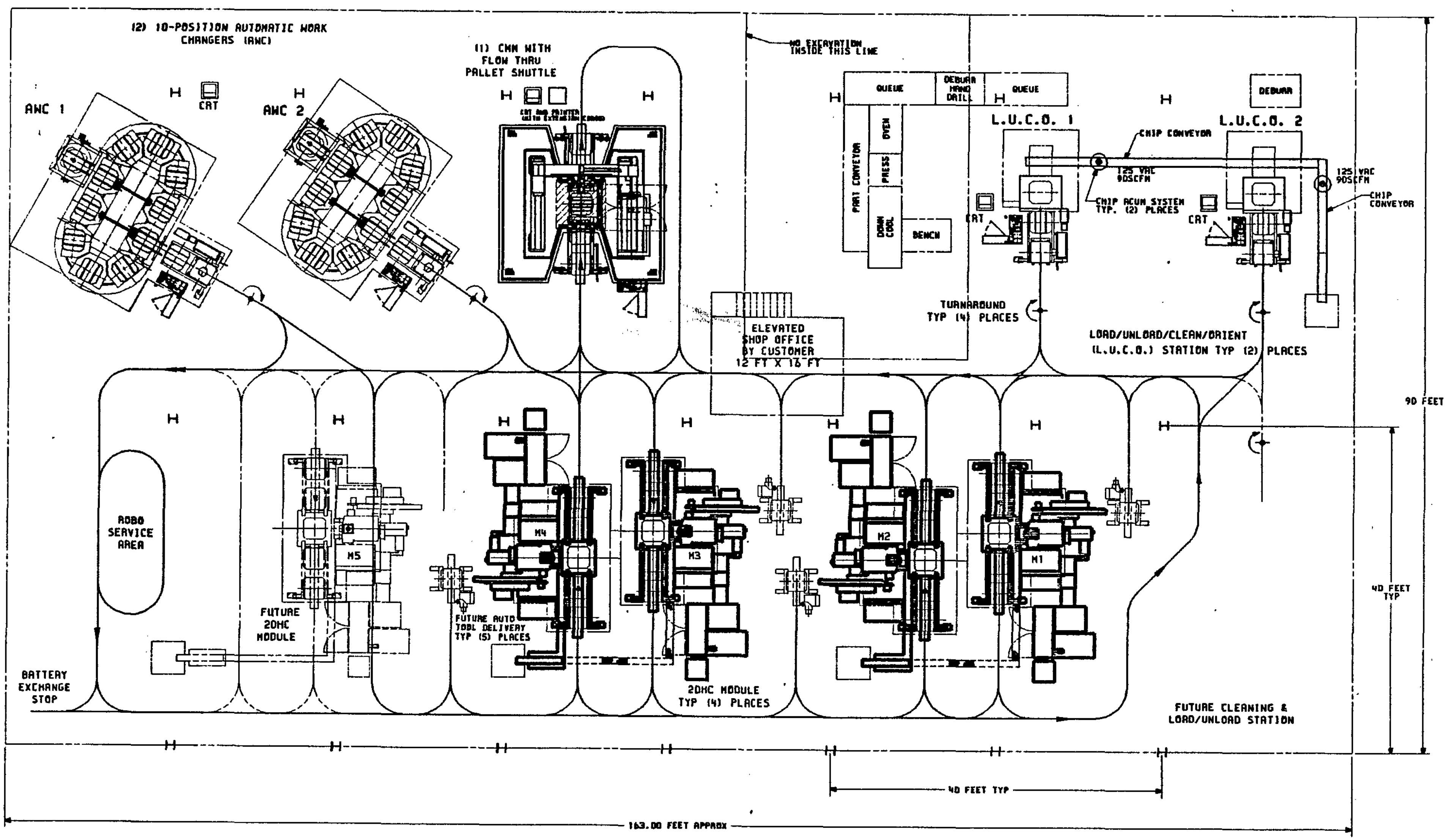

Figure 1. Client FMS Layout

3.0 SEVEN SCENARIOS

3.1 TOOLBAL RUNS

Using data on tooling, fixturing, on-machine gauging times, and operation times which were available in January 1984, a series of TOOLBAL and simulation runs were made. (See Table 1 on page 9 for part tool data.) Presented here are seven scenarios or configurations which represent the best of those runs. Six of those tool assignment configurations are single-parts group scenarios; the seventh is a two-parts group scenario.

Table 2 on page 10 describes the seven configurations studied. Note that Configurations 1, 2, 3, 4 and 7 assume that all four machining centers are operational. Configuration 5 assumes that one of the four machines is unavailable; the entire workload is processed on the remaining three machines. In Configuration 6 it is assumed that five machines are up, i.e., an additional machine has been added to the current configuration.

Configuration 7 was the only configuration in which all five of the critical parts could be duplicately tooled. However, in order to achieve this, two parts groups were required due to the tool storage constraints of the machines. Configuration 5, the three-machine scenario, is the "fall-back" configuration for the several four-machine configurations. If the "fourth" machine in Configurations 3 or 4 fails, then no tool changing is required; the system automatically becomes Configuration 5. Otherwise, some tool changing would be required.

Table 3 on page 11 shows, for each of the seven configurations, the machine assignments for each of the 23 fixturings. The paired columns for Configuration 7 shows the assignments for each of the two parts groups. All of these assignments were generated by the "tool allocation and workload balancing" program, TOOLBAL. The top five rows of Table 4 on page 12 show the number of tool pockets utilized (of 89 available) on each of the machines for Configurations 1 through 6. (Note that some of the tools require three pockets due to their size, and the pocket totals do not include a 90th pocket used for a touch probe at each machine.)

3.2 SIMULATION RUNS

Table 4 on page 12 plus Table 5 on page 13 present the results of simulation runs for six configurations. The simulation runs were made using the data specified in Table 1 on page 9 and Table 3 on page 11. One out of ten occurrences of each route went to the inspection station

Table 1. Client Parts Data

C	PART NUMBER	PART NAME	PROD-QUANT MO	PROD-QUANT WK	CRIT PART	ROUTE NUMBR	ROUTE NAME	FIXTURE NAME	# FINISH PARTS/RT	LUCO
C										
	12276462	ROTOR-FACEPLATE	55	14	Y	1	6462	F6462	1	1
	12293284-1	FINAL DRIVE HOUSING	118	30	Y	2	32841	F32841	1	1
	12293284-2	FINAL DRIVE COVER	118	30	Y	3	32842A	F32842A	1	1
						4	32842B	F32842B	1	1
	12293284	FINAL DRIVE ASSY	118	30	Y	5	3284	F3284	1	1
C										
	12294593-S	PLATE-SIDE TURRET	55	14	N	6	4593S	F4593S	1	1
	12294615	LEFT HAND TRUNNION	55	14	N	7	4615	F4615	1	1
	12294646	GEAR BOX ADAPTOR	59	15	N	8	4646	F4646	2	2,1
	12294765	P.T.O. HOUSING	59	15	Y	9	4765A	F4765A	1	1
						10	4765B	F4765B	1	1
C										
	12294887-3	TRANS MTG SUPPORT	59	15	N	11	48873	F48873	1	2,1
	12294887-4	TRANS MTG SUPPORT	59	15	N	12	48874	F48874	1	2,1
	12296954	LONG ENG SUPPORT	118	30	N	13	6954	F6954	1	2,1
	12298622	FLUID COUP HOUSING	59	15	N	14	8622A	F8622A	2	2,1
						15	8622B	F8622B	2	2,1
C										
	12308936	ACCESS DOOR HINGE	110	28	N	16	8936	F0001	2	2,1
	12295270	ACCESS DOOR HINGE	110	28	N	17	5270	F0001	2	2,1
	12308498	RAMP HINGE	110	28	N	18	8498	F0001	2	2,1
	12317037	LAUNCH SUPP BRACKET	55	14	N	19	7037	F7037	1	2,1
	12328805	IDLER WHEEL ARM	118	30	N	20	8805	F8805	1	2,1
C										
	12316840	GUNNER HATCH COVER	55	14	N	21	6840	F6840	1	1
	12316841	COMMR HATCH COVER	55	14	N	22	6841A	F6841A	1	1
						23	6841B	F6841B	1	1

Table 2. Description of the Seven Tool Allocation Configurations

Configuration 1:	Four machines up; all of the parts are tooled with single redundancy except four of the five critical parts which are tooled dually redundant, i.e., tool sets provided on two different machines. (The rotor-faceplate is not duplicately tooled.)
Configuration 2:	Same as Configuration 1 except that the PTO housing is the only critical part not duplicately tooled.
Configuration 3:	Four machines up; all of the parts are tooled with single redundancy on three of the machines, and four of five critical part are duplicately tooled on the fourth machine. (The rotor-faceplate is not duplicately tooled.)
Configuration 4:	Same as Configuration 3 except that the PTO housing is the only critical part not duplicately tooled.
Configuration 5:	Three machines up; all of the parts are tooled with single redundancy on the three machines.
Configuration 6:	Five machines up; all parts are tooled with single redundancy except the five critical parts which are duplicately tooled.
Configuration 7:	Four machines up; two parts groups; all parts are tooled with single redundancy except the five critical parts which are duplicately tooled and appear in both parts groups.

following a three-minute clean/debur operation at a load/unload station. The simulation runs completed when the weekly production quantities for all of the parts were produced. Two production levels were simulated: 55 vehicles/month (Table 1 on page 9) and 75 vehicles/month. At the 55 vehicles/month rate two sets of runs were made; one set with but one fixture of each type (for a total of 21) and a second set with additional fixtures for the two longest-time-in-system fixtures, namely, the Idler Wheel Arm and the Hinge fixtures (for a total of 23 fixtures).

Table 3. Machining Operation Assignments for Seven Tool Configurations

PART NUMBER	PART NAME	PROD-QUANT MO	PROD-QUANT WK	CRIT PART	ROUTE NUMBR	ROUTE NAME	FIXTURE NAME	--- 20HC MACHINE ASSIGNMENTS --- CONFIG.1	CONFIG.2	CONFIG.3	CONFIG.4	CONFIG.5	CONFIG.6	CONFIG.7 B/1	CONFIG.7 B/2
12276462	ROTOR-FACEPLATE	55	14	Y	1	6462	F6462	2	3,4	3	3,4	3	1,5	1,2	1,2
12293284-1	FINAL DRIVE HOUSING	118	30	Y	2	32841	F32841	3,4	2,1	1,4	1,4	1	2,3	3,4	3,4
12293284-2	FINAL DRIVE COVER	118	30	Y	3	32842A	F32842A	3,4	1,2	1,4	1,4	1	2,3	1,2	1,2
					4	32842B	F32842B	1,3	1,4	3,4	3,4	3	1,5	1,2	1,2
12293284	FINAL DRIVE ASSY	118	30	Y	5	3284	F3284	2,4	1,2	1,4	1,4	1	1,5	3,4	3,4
12294593-S	PLATE-SIDE TURRET	55	14	N	6	4593S	F4593S	3	4	3	3	3	5	4	
12294615	LEFT HAND TRUNNION	55	14	N	7	4615	F4615	1	1	2	2	2	4	4	
12294646	GEAR BOX ADAPTOR	59	15	N	8	4646	F4646	1	3	2	2	2	1		2
12294765	P.T.O. HOUSING	59	15	Y	9	4765A	F4765A	1,2	1	1,4	1	1	1,2	1,2	1,2
					10	4765B	F4765B	3,4	2	2,4	2	2	4,3	3,4	3,4
12294887-3	TRANS MTG SUPPORT	59	15	N	11	48873	F48873	1	1	1	1	1	3	3	
12294887-4	TRANS MTG SUPPORT	59	15	N	12	48874	F48874	1	1	1	1	1	2	3	
12296954	LONG ENG SUPPORT	118	30	N	13	6954	F6954	3	1	1	1	1	2	3	
12298622	FLUID COUP HOUSING	59	15	N	14	8622A	F8622A	2	1	2	2	2	2	4	
					15	8622B	F8622B	4	2	2	2	2	3	2	
12308936	ACCESS DOOR HINGE	110	28	N	16	8936	F0001	4	3	2	2	2	3		4
12295270	ACCESS DOOR HINGE	110	28	N	17	5270	F0001	4	3	2	2	2	2		3
12308498	RAMP HINGE	110	28	N	18	8498	F0001	4	4	2	2	2	3		1
12317037	LAUNCH SUPP BRACKET	55	14	N	19	7037	F7037	2	4	3	3	3	5	2	
12328805	IDLER WHEEL ARM	118	30	N	20	8805	F8805	1	3	3	3	3	4	1	
12316840	GUNNER HATCH COVER	55	14	N	21	6840	F6840	2	2	1	1	1	1	3	
12316841	COMMR HATCH COVER	55	14	N	22	6841A	F6841A	3	2	1	1	1	5	3	
					23	6841B	F6841B	3	2	1	1	1	2	3	

Table 4. Tool Chain Utilizations and Weekly Production Completion Times for Six Tool Configurations

TOOL CHAIN UTILIZATIONS AND WEEKLY PRODUCTION COMPLETION TIMES FOR 6 TOOL CONFIGURATIONS							
		CONFIG. 1	CONFIG. 2	CONFIG. 3	CONFIG. 4	CONFIG. 5	CONFIG. 6
NUMBER OF TOOL POCKETS UTILIZED ON MACHINE	M1	77	84	80	80	80	86
	M2	87	79	88	88	88	82
	M3	88	76	79	79	79	83
	M4	88	76	78	74	0	60
	M5	--	--	--	--	--	82
55 VEH./MO. 21 FIXTURES	Time to Complete Wk. Prod. (Min.)	4346	4486	5492	4412	6122	3947
	% of Avail. Time	60.3	62.3	76.2	61.2	85.0	54.8
55 VEH./MO. 23 FIXTURES	Time to Complete Wk. Prod. (Min.)	4192	4452	5176	4430	6249	3792
	% of Avail. Time	58.2	61.8	71.8	61.5	86.7	52.6
75 VEH./MO. 21 FIXTURES	Time to Complete Wk. Prod. (Min.)	5814	5963	7401	6084	8202	5101
	% of Avail. Time	80.7	82.8	102.7	84.5	113.9	70.8

Table 5. Percent Utilization of System Resources at End of Each of the First Three 24-Hour Periods (55 Vehicles/Month)

PERCENT UTILIZATION OF SYSTEM RESOURCES AT END OF EACH OF THE FIRST THREE 24 HOUR PERIODS (55 veh/mo)																		
	CONFIG 1			CONFIG 2			CONFIG 3			CONFIG 4			CONFIG 5			CONFIG 6		
	1440 (Min)	2880 (Min)	4320 (Min)	1440 (Min)	2880 (Min)	4320 (Min)	1440 (Min)	2880 (Min)	4320 (Min)	1440 (Min)	2880 (Min)	4320 (Min)	1440 (Min)	2880 (Min)	4320 (Min)	1440 (Min)	2880 (Min)	4320 (Min)
M1	99	99	93	98	99	92	98	97	77	98	99	81	98	99	99	84	84	62
M2	99	99	86	95	97	97	99	89	67	99	92	73	99	93	82	91	84	65
M3	97	95	79	97	97	97	99	99	98	99	98	94	99	99	98	94	91	71
M4	92	96	84	96	80	55	93	96	81	91	95	93	0	0	0	90	92	80
M5		--			--			--			--			--		87	85	65
INSP.	23	21	17	20	18	16	23	20	16	21	20	17	21	16	14	23	22	17
LUCO1	73	72	61	72	67	62	76	74	61	71	70	62	61	57	52	81	79	61
LUCO2	62	58	47	56	51	45	65	54	43	63	55	46	47	41	37	77	63	47
CART	66	58	46	68	65	53	69	59	46	67	63	49	67	62	54	60	53	54

Using the vendor-recommended criterion that the weekly production should be completed in 70% or less of the available time (5040 out of 7200 minutes), Table 4 on page 12 indicates that Configurations 1, 2, 4 and 6 would be acceptable at the 55 vehicle/month production level. At the 75 vehicle/month level, only Configuration 6 is satisfactory and only marginally so. The addition of two extra fixtures provided little or no improvement in each of the six configurations, primarily because they are not tooled redundantly. Table 5 on page 13 shows for the six configurations, the simulation-predicted utilization of system resources for the "55 vehicle/month - 21 fixture" case. The percent utilization figures are presented for the first 24 hours, the first 48 hours, and the first 72 hours. The data indicates that the machines are well utilized at the beginning of the week and become less so as the production requirements are met towards the end of the week. The inspection station, the two load/unload stations, and the carts are less utilized.

Table 6 on page 15 presents by means of a "bar chart" when each machine completed its work, for each of the seven configurations. The pattern for each configuration suggests how well the total workload is balanced across the machines. Note that for Configuration 7, it is assumed that a maximum of 100 minutes will be required for tool changeover time between parts groups on each machine.

3.3 THE "TWO-PARTS GROUP" SCENARIO

Shown in Table 7 on page 16 are TOOLBAL and simulation results for the two-parts group scenario, Configuration 7, similar to those shown in Table 4 on page 12 and Table 5 on page 13 . This scenario arose from the desire to have all five critical parts duplicately tooled (producible on two machines) at all times. TOOLBAL could not satisfy this requirement and still fit the tools for the remaining parts into the system. Thus a second parts group was needed.

For Configuration 7, Table 3 on page 11 shows which parts would be produced in each of the two parts groups, and which machines they would go to. Table 8 on page 17 lists the parts and the tools required for each setup. Table 9 on page 19 and Table 10 on page 21 show for Parts Group 1 and Parts Group 2 the portion of TOOLBAL's output that tells which tools are on which machines.

If duplicate tooling for all five of the critical parts is not an absolute requirement, Table 6 on page 15 suggests that Configuration 7 would not be a good choice. With the exception of Configuration 5 (the three-machine scenario), Configuration 7 takes the longest time to complete the week's production. This is primarily due to the low machine utilization in Parts Group 2, and this in turn is due to the relative lack of fixtures in the system. Also, all three hinges are in Parts Group 2, but since they alternately share the same pallet/fixture, they

Table 6. Machine Loading for Week's Production Run (55 Vehicle/Month Rate) for Seven Tool Configurations.

```
                          MACHINE LOADING FOR WEEKS' PRODUCTION RUN
                          (55VEH/MO RATE) FOR SEVEN TOOL CONFIGURATIONS

       DAYS   <--- DAY 1 ---><--- DAY 2 --><--- DAY 3 --><--- DAY 4 ---><--- DAY 5 --->
   THOUS MINS 0         1         2         3         4         5         6         7
              |....+....|....+....|....+....|....+....|....+....|....+....|....+....|..

          M1  |*******************************************
CONFIG    M2  |****************************************
  1       M3  |**************************************
          M4  |*****************************************

              |....+....|....+....|....+....|....+....|....+....|....+....|....+....|..

          M1  |********************************************
CONFIG    M2  |*********************************************
  2       M3  |*********************************************
          M4  |*******************************************

              |....+....|....+....|....+....|....+....|....+....|....+....|....+....|..

          M1  |***************************************
CONFIG    M2  |************************************
  3       M3  |*******************************************************
          M4  |**************************************

              |....+....|....+....|....+....|....+....|....+....|....+....|....+....|..

          M1  |********************************************
CONFIG    M2  |*************************************
  4       M3  |********************************************
          M4  |******************************************

              |....+....|....+....|....+....|....+....|....+....|....+....|....+....|..

          M1  |*************************************************************
CONFIG    M2  |******************************************
  5       M3  |***********************************************************

              |....+....|....+....|....+....|....+....|....+....|....+....|....+....|..

          M1  |************************************
CONFIG    M2  |***********************************
  6       M3  |***********************************
          M4  |***************************************
          M5  |************************************

              |....+....|....+....|....+....|....+....|....+....|....+....|....+....|..

          M1  |*****************************************T*********          T = TOOL
CONFIG    M2  |***********************************T******                    CHANGE-
  7       M3  |************************************T********************     OVER
          M4  |***********************************T***************           TIME

              |....+....|....+....|....+....|....+....|....+....|....+....|....+....|..
   THOUS MINS 0         1         2         3         4         5         6         7
```

Table 7. Results for the Two-Parts Group Scenario, Configuration 7

	Parts Group 1	Parts Group 2	
M1	80	77	No. of
M2	87	80	Tool
M3	89	68	Pockets
M4	88	69	Used
Time To Complete Weekly Prod. (Min.)	4153	2017	55 Veh/Mo. 21 Fixtures

	Parts Group 1			Parts Group 2		
	1440 (Min.)	2880 (Min.)	4320 (Min.)	1440 (Min.)	2880 (Min.)	4320 (Min.)
	% Utilization			% Utilization		
M1	99	93	86	47	24	16
M2	95	78	57	33	17	11
M3	99	95	70	42	23	15
M4	98	99	79	21	19	13

must be done sequentially. This substantially lengthens the time to complete that parts group compared with what would be the case if duplicate fixtures were available or all three hinges were on the same fixture. (Note: The capability to put three different hinge types on the single fixture for a single routing dispatch is being pursued by the vendor.)

Table 8. TOOLBAL Input Tool List (Part 1 of 2)

PART#	SEG.#	MAC.CODE	REDUN	REQ.TOOLS	TOOL LIST					
6462	1	1	2	33	155	161	162	168	171	172
					173	175	176	181	183	184
					185	189	190	191	192	194
					201	204	206	206	208	210
					217	222	226	2130	2131	2132
					2140	2141	2142			
3284	1	1	2	15	10	40	47	49	64	65
					66	67	68	69	70	71
					72	73	74			
32841	1	1	2	21	10	17	18	40	41	44
					47	49	51	52	54	56
					58	59	60	61	62	63
					79	80	152			
32842	1	1	2	16	10	29	40	43	44	45
					47	48	49	51	52	53
					54	55	56	80		
	2	1	2	5	10	41	78	101	149	
4593	1	1	1	16	10	41	43	104	130	132
					135	137	138	139	1440	1441
					1442	1500	1501	1502		
4615	1	1	1	16	17	18	46	47	49	52
					81	95	99	133	140	141
					152	1430	1431	1432		
4646	1	1	1	18	5	10	25	31	40	48
					51	108	109	110	111	122
					123	124	125	131	142	153
4765	1	1	2	17	4	6	7	8	9	10
					11	12	13	14	15	16
					21	40	41	42	52	
	2	1	2	31	5	10	13	17	18	19
					20	22	24	25	26	27
					28	29	30	31	32	33
					34	35	36	37	38	39
					40	57	75	76	77	152
					208					

Table 8. TOOLBAL Input Tool List (Part 2 of 2)

48873	1	1	1	12	8	10	40	41	90	92
					105	132	146	1450	1451	1452
48874	1	1	1	14	8	10	40	41	90	92
					105	132	146	148	153	1450
					1451	1452				
8936	1	1	1	11	146	163	169	172	178	179
					224	228	2230	2231	2232	
5270	1	1	1	11	146	156	163	166	169	172
					208	222	2230	2231	2232	
8498	1	1	1	12	146	147	157	164	165	182
					196	216	222	2230	2231	2232
7037	1	1	1	22	161	170	172	174	177	184
					188	191	193	205	207	211
					215	218	219	221	222	226
					227	2130	2131	2132		
6954	1	1	1	19	17	18	41	43	47	49
					81	91	93	94	99	104
					131	134	136	152	1450	1451
					1452					
8622	1	1	1	12	6	7	10	13	21	40
					106	107	151	1430	1431	1432
	2	1	1	12	5	13	31	32	40	41
					77	95	127	128	129	208
8805	1	1	1	17	167	172	180	186	187	195
					197	198	199	200	202	203
					208	209	210	212	224	
6841	1	1	1	6	10	47	49	902	903	904
	2	1	1	13	10	17	18	47	49	132
					904	905	906	907	908	909
					910					
6840	1	1	1	8	10	17	18	47	49	131
					901	902				

Table 9. Configuration 7 - Parts Group 1 Machine Assignments (Part 1 of 2)

MACHINE: 1

PART#	SEGMENT#	REDUNDANCY	TOTAL TIME
6462	1	2	2373.99
32842	1	2	1369.13
32842	2	2	285.44
4765	1	2	746.87
8805	1	1	9617.00

SUM TOTAL TIME 14392.43

TOTAL NO.OF TOOLS 80

TOOLS REQUIRED ON MACHINE: 1

4	6	7	8	9	10
11	12	13	14	15	16
21	29	40	41	42	43
44	45	47	48	49	51
52	53	54	55	56	78
80	101	149	155	161	162
167	168	171	172	173	175
176	180	181	183	184	185
186	187	189	190	191	192
194	195	197	198	199	200
201	202	203	204	206	206
208	209	210	212	217	222
224	226	2130	2131	2132	2140
2141	2142				

MACHINE: 2

PART#	SEGMENT#	REDUNDANCY	TOTAL TIME
6462	1	2	2373.99
32842	1	2	1369.13
32842	2	2	285.44
4765	1	2	746.87
7037	1	1	3137.20
8622	2	1	1602.00

SUM TOTAL TIME 9514.63

TOTAL NO.OF TOOLS 87

TOOLS REQUIRED ON MACHINE: 2

4	5	6	7	8	9
10	11	12	13	14	15
16	21	29	31	32	40
41	42	43	44	45	47
48	49	51	52	53	54
55	56	77	78	80	95
101	127	128	129	149	155
161	162	168	170	171	172
173	174	175	176	177	181
183	184	185	188	189	190
191	192	193	194	201	204
205	206	206	207	208	210
211	215	217	218	219	221
222	226	227	2130	2131	2132
2140	2141	2142			

Table 9. Configuration 7 - Parts Group 1 Machine Assignments (Part 2 of 2)

MACHINE: 3

PART#	SEGMENT#	REDUNDANCY	TOTAL TIME
3284	1	2	2163.90
32841	1	2	2323.75
4765	2	2	1558.27
6954	1	1	2481.54
6840	1	1	1419.00
48874	1	1	1157.58
6841	2	1	1058.20
48873	1	1	997.10
6841	1	1	908.05

SUM TOTAL TIME 14067.38

TOTAL NO.OF TOOLS 89

TOOLS REQUIRED ON MACHINE: 3

5	8	10	13	17	18
19	20	22	24	25	26
27	28	29	30	31	32
33	34	35	36	37	38
39	40	41	43	44	47
49	51	52	54	56	57
58	59	60	61	62	63
64	65	66	67	68	69
70	71	72	73	74	75
76	77	79	80	81	90
91	92	93	94	99	104
105	131	132	134	136	146
148	152	153	208	901	902
903	904	905	906	907	908
909	910	1450	1451	1452	

MACHINE: 4

PART#	SEGMENT#	REDUNDANCY	TOTAL TIME
3284	1	2	2163.90
32841	1	2	2323.75
4765	2	2	1558.27
4615	1	1	2081.75
4593	1	1	1712.70
8622	1	1	1119.30

SUM TOTAL TIME 10959.67

TOTAL NO.OF TOOLS 88

TOOLS REQUIRED ON MACHINE: 4

5	6	7	10	13	17
18	19	20	21	22	24
25	26	27	28	29	30
31	32	33	34	35	36
37	38	39	40	41	43
44	46	47	49	51	52
54	56	57	58	59	60
61	62	63	64	65	66
67	68	69	70	71	72
73	74	75	76	77	79
80	81	95	99	104	106
107	130	132	133	135	137
138	139	140	141	151	152
208	1430	1431	1432	1440	1441
1442	1500	1501	1502		

PARTS GROUP# 1 SUMMARY

MACHINE	TOTAL TIME	TOTAL TOOLS
1	14392.434	80
2	9514.629	87
3	14067.383	89
4	10959.668	88

AVERAGE MACHINE UTILIZATION	AVERAGE TOOL UTILIZATION	TOTAL NUMBER OF TOOLS
0.850	0.966	344

Table 10. Configuration 7 - Parts Group 2 Machine Assignments (Part 1 of 2)

MACHINE: 1

PART#	SEGMENT#	REDUNDANCY	TOTAL TIME
6462	1	2	447.51
32842	1	2	258.09
32842	2	2	53.81
4765	1	2	140.79
8498	1	1	1371.70

SUM TOTAL TIME 2271.89

TOTAL NO.OF TOOLS 77

MACHINE: 2

PART#	SEGMENT#	REDUNDANCY	TOTAL TIME
6462	1	2	447.51
32842	1	2	258.09
32842	2	2	53.81
4765	1	2	140.79
4646	1	1	1364.40

SUM TOTAL TIME 2264.59

TOTAL NO.OF TOOLS 80

TOOLS REQUIRED ON MACHINE: 1

4	6	7	8	9	10
11	12	13	14	15	16
21	29	40	41	42	43
44	45	47	48	49	51
52	53	54	55	56	78
80	101	146	147	149	155
157	161	162	164	165	168
171	172	173	175	176	181
182	183	184	185	189	190
191	192	194	196	201	204
206	206	208	210	216	217
222	226	2130	2131	2132	2140
2141	2142	2230	2231	2232	

TOOLS REQUIRED ON MACHINE: 2

4	5	6	7	8	9
10	11	12	13	14	15
16	21	25	29	31	40
41	42	43	44	45	47
48	49	51	52	53	54
55	56	78	80	101	108
109	110	111	122	123	124
125	131	142	149	153	155
161	162	168	171	172	173
175	176	181	183	184	185
189	190	191	192	194	201
204	206	206	208	210	217
222	226	2130	2131	2132	2140
2141	2142				

Table 10. Configuration 7 - Parts Group 2 Machine Assignments (Part 2 of 2)

MACHINE: 3

PART#	SEGMENT#	REDUNDANCY	TOTAL TIME
3284	1	2	407.91
32841	1	2	438.04
4765	2	2	293.74
5270	1	1	1343.10

SUM TOTAL TIME 2482.78

TOTAL NO.OF TOOLS 68

MACHINE: 4

PART#	SEGMENT#	REDUNDANCY	TOTAL TIME
3284	1	2	407.91
32841	1	2	438.04
4765	2	2	293.74
8936	1	1	1065.35

SUM TOTAL TIME 2205.03

TOTAL NO.OF TOOLS 69

TOOLS REQUIRED ON MACHINE: 3

5	10	13	17	18	19
20	22	24	25	26	27
28	29	30	31	32	33
34	35	36	37	38	39
40	41	44	47	49	51
52	54	56	57	58	59
60	61	62	63	64	65
66	67	68	69	70	71
72	73	74	75	76	77
79	80	146	152	156	163
166	169	172	208	222	2230
2231	2232				

TOOLS REQUIRED ON MACHINE: 4

5	10	13	17	18	19
20	22	24	25	26	27
28	29	30	31	32	33
34	35	36	37	38	39
40	41	44	47	49	51
52	54	56	57	58	59
60	61	62	63	64	65
66	67	68	69	70	71
72	73	74	75	76	77
79	80	146	152	163	169
172	178	179	208	224	228
2230	2231	2232			

PARTS GROUP# 2 SUMMARY

MACHINE	TOTAL TIME	TOTAL TOOLS
1	2271.889	77
2	2264.589	80
3	2482.782	68
4	2205.032	69

AVERAGE MACHINE UTILIZATION	AVERAGE TOOL UTILIZATION	TOTAL NUMBER OF TOOLS
0.929	0.826	294

Table 11. Configuration 7 Tool Changeover Assignments - Parts Group 1 to Parts Group 2 (Part 1 of 2)

REMOVE THESE TOOLS FROM MACHINE 1 :
167
180
186
187
195
197
198
199
200
202
203
209
212
224
(ALTOGETHER 14 TOOLS)

REMOVE THESE TOOLS FROM MACHINE 2 :
32
77
95
127
128
129
170
174
177
188
193
205
207
211
215
218
219
221
227
(ALTOGETHER 19 TOOLS)

PUT THESE TOOLS ONTO MACHINE # 1 :
146
147
157
164
165
182
196
216
2230
2231
2232
(ALTOGETHER 11 TOOLS)

PUT THESE TOOLS ONTO MACHINE # 2 :
25
108
109
110
111
122
123
124
125
131
142
153
(ALTOGETHER 12 TOOLS)

Table 11. Configuration 7 Tool Changeover Assignments - Parts Group 1 to Parts Group 2 (Part 2 of 2)

REMOVE THESE TOOLS FROM MACHINE 3 :
8
43
81
90
91
92
93
94
99
104
105
131
132
134
136
148
153
901
902
903
904
905
906
907
908
909
910
1450
1451
1452
(ALTOGETHER 30 TOOLS)

REMOVE THESE TOOLS FROM MACHINE 4 :
6
7
21
43
46
81
95
99
104
106
107
130
132
133
135
137
138
139
140
141
151
1430
1431
1432
1440
1441
1442
1500
1501
1502
(ALTOGETHER 30 TOOLS)

PUT THESE TOOLS ONTO MACHINE # 3 :
163
169
172
178
179
224
228
2230
2231
2232
(ALTOGETHER 10 TOOLS)

PUT THESE TOOLS ONTO MACHINE # 4 :
146
156
163
166
169
172
222
2230
2231
2232
(ALTOGETHER 10 TOOLS)

3.4 TOOL CHANGEOVERS

Of course, an additional reason that Configuration 7 is not desirable is that tool changeovers are required between parts groups. Table 11 on page 23 shows the tools to be removed from each machine and the tools to place on each machine during the transition from Parts Group 1 to Parts Group 2. This information was generated by Draper's "TOOL CHANGE" program which used as its input the output of TOOLBAL.

TOOL CHANGE examines TOOLBAL's machine assignments and attempts to minimize the number of cutting tools which must be handled. In doing so, it may decide to "renumber" the machines as assigned in Parts Group 2 by TOOLBAL. This can happen because TOOLBAL does not address tool changeovers. The parts assigned to a specific machine in one parts group generally have little or no relation to the parts (and tools) assigned to the same machine in another parts group. TOOL CHANGE looks at the tools on each machine for a given parts group and the tools needed on each machine for the subsequent parts group, and makes the best match in order to reduce total tool handling at Parts Group transition. Thus for Configuration 7, Machines 1 and 2 in Parts Group 2 were the same as Machines 1 and 2 in Parts Group 1. But, Machines 3 and 4 were swapped; that is, to minimize tool movement, what TOOLBAL called Machine 3 in Parts Group 2 would be the same as Parts Group 1's Machine 4, according to TOOL CHANGE.

As a further example of the use of TOOL CHANGE Table 12 on page 26 through Table 14 on page 28 show the required tool changeovers in going from Configuration 4 to Configuration 5. This transition would occur if one of the four machines of Configuration 4 failed and it was predicted to be down for an appreciable time. If Machine 4 failed, then no tool swapping would be required because the remaining three machines are tooled precisely the way in which they would be in Configuration 5. (Machine 4 contains only the redundant tooling for four critical parts; see Table 3 on page 11.)

If Machine 1 fails, then its work should be shifted to Machine 4, i.e., the tools on Machine 1 which are not duplicated on Machine 4 must be moved to the still-operating machine #4 and room made for them. Similar actions are required if Machine 2 or Machine 3 fails. These transition scenarios are depicted in Table 12 on page 26 through Table 14 on page 28, respectively.

Table 12. Tool Changeover, Configuration 4 to Configuration 5, Machine 1 Failed

REMOVE THESE TOOLS FROM MACHINE 4 :	PUT THESE TOOLS ONTO MACHINE # 4 :
78	4
101	6
149	7
155	8
161	9
162	11
168	12
171	13
172	14
173	15
175	16
176	21
181	42
183	81
184	90
185	91
189	92
190	93
191	94
192	99
194	104
201	105
204	131
206	132
206	134
208	136
210	146
217	148
222	153
226	901
2130	902
2131	903
2132	904
2140	905
2141	906
2142	907
(ALTOGETHER 36 TOOLS)	908
	909
	910
	1450
	1451
	1452
	(ALTOGETHER 42 TOOLS)

Table 13. Tool Changeover, Configuration 4 to Configuration 5, Machine 2 Failed

REMOVE THESE TOOLS FROM MACHINE 4 :

43	155
44	161
45	162
53	168
54	171
55	173
56	175
58	176
59	181
60	183
61	184
62	185
63	189
64	190
65	191
66	192
67	194
68	201
69	204
70	206
71	206
72	210
73	217
74	226
78	2130
79	2131
80	2132
101	2140
149	2141
	2142

(ALTOGETHER 59 TOOLS)

PUT THESE TOOLS ONTO MACHINE # 4 :

5	111
6	122
7	123
13	124
19	125
20	127
21	128
22	129
24	131
25	133
26	140
27	141
28	142
30	146
31	147
32	151
33	153
34	156
35	157
36	163
37	164
38	165
39	166
46	169
57	178
75	179
76	182
77	196
81	216
95	224
99	228
106	1430
107	1431
108	1432
109	2230
110	2231
	2232

(ALTOGETHER 73 TOOLS)

Table 14. Tool Changeover, Configuration 4 to Configuration 5, Machine 3 Failed

REMOVE THESE TOOLS FROM MACHINE 4 :

17
18
29
40
44
45
47
48
49
51
52
53
54
55
56
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
79
80
152

(ALTOGETHER 35 TOOLS)

PUT THESE TOOLS ONTO MACHINE # 4 :

104
130
132
135
137
138
139
167
170
174
177
180
186
187
188
193
195
197
198
199
200
202
203
205
207
209
211
212
215
218
219
221
224
227
1440
1441
1442
1500
1501
1502

(ALTOGETHER 40 TOOLS)

These tables thus provide client with a pre-planned response to out-of-service machines if the machines are tooled as defined in Configuration 4. Configuration 4 is preferred over the other configurations because it has the dual advantage of producing parts within the nominal 70% of monthly time available, and substantially easing the out-of-service machine retooling scenarios.